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RICE UNIVERSITY

Cosmic Rays in Active Galactic Nuclei

by

Mercè Crosas

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

Doctor of Philosophy

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February, 1994
Abstract

Cosmic Rays in Active Galactic Nuclei

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This work explores the connection between cosmic rays and light element production in an active galaxy environment.

Cosmic rays generated in an active galactic nucleus (AGN) interact with the local, line-emitting gas and spall the light elements, Li, Be and B. Careful consideration of the propagation of cosmic rays from AGNs to Earth yields a variety of models that are consistent with the observed cosmic ray spectrum. However, by using observed upper limits for BIII $\lambda$2066Å line emission from AGNs, we are able to rule out certain cosmic ray flux models. This analysis requires a detailed study of boron ionization balance under typical AGN conditions, a study that is carried out here for the first time. Models with a total cosmic ray luminosity $L_{CR} = 10^{45}$ erg s$^{-1}$ and a diffusion coefficient in the line emission region of $D \leq 10^{28}$ cm$^2$ s$^{-1}$, and those with $L_{CR} = 10^{45}$ erg s$^{-1}$ and $D \leq 3 \times 10^{26}$ cm$^2$ s$^{-1}$ do not satisfy the spectroscopic constraints. However, models with lower cosmic ray luminosities or larger diffusion coefficients are acceptable.

The results of spallation in AGNs are also applied to our Galaxy, under the assumption that it has passed through an active phase. An additional source of light elements during this active phase can reproduce the B and Be abundances observed in the halo, and contribute partially to the light element abundances observed in the disk.
Acknowledgments

I wish to express my gratitude to the following people who made the completion of this thesis possible:

My thesis advisor, Jon Weisheit, for his outstanding job as a teacher, mentor and collaborator. Throughout my graduate career he was always supportive and understanding.

Professors E. P. Liang and R. C. Haymes, members of my committee, for providing many helpful comments and advice. Their careful reading of my thesis is deeply appreciated.

The Ministry of Education and Science of Spain and the U. S. National Science Foundation for the financial support.

The staff members of the Space Physics and Astronomy Department at Rice University for their constant help, especially Umbe and Maria for always being close to me, even before they met me.

The students Don Walter, Patrick Shopbell and Hui Li for stimulating discussions and computational help.

Alex Dalgarno and Kate Kirby who made my stay at ITAMP of the Harvard-Smithsonian Center for Astrophysics, both possible and enjoyable.

The Cardus family for helping and supporting me since the moment I met them. They always treated me as part of their family while I was away from home.

My family for their encouragement, unconditional love and moral support, especially my mother for her many calls and visits during all the years of my graduate work.
Lance for devoting so much care, helping to improve my writing in a foreign language, and his never ending intellectual stimulation and patience.
A la mare, al pare i als germans pel seu amor constant
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Chapter 1

INTRODUCTION

A knowledge of the cosmic ray flux in Active Galactic Nuclei (AGNs) is important not only for understanding the AGN central engine, but also for studying the evolution of light element abundances and the cosmic ray activity in young galaxies. In this work, we estimate upper limits for the cosmic ray flux in radio-quiet AGNs by examining the interaction between these energetic particles and the AGN gas. When the local cosmic rays encounter the H, He, C, N and O nuclei that exist in the extended narrow line region (NLR) of the AGN, Li, Be and B are produced through spallation reactions. Since there are no other processes that can efficiently form these light elements (except for $^7\text{Li}$, which is formed by primordial nucleosynthesis in the Big Bang), the spallation products in the NLR provide direct information about the amount of cosmic rays originating in the central region of an AGN.

Before computing the spallation products in the NLR as a function of the cosmic ray flux in the AGN, we first find a range of possible values for this cosmic ray flux and evaluate its characteristics. In Chapter 2, we describe the properties of the cosmic rays observed at Earth, and relate them to the cosmic rays coming from AGNs. We show that cosmic rays originating in AGNs at large distances from Earth (> 100 Mpc) do not contribute to the observed spectrum. In Chapter 3, we discuss possible sources and acceleration mechanisms of cosmic rays in AGNs. We obtain upper limits for the AGN cosmic ray luminosity by considering first the efficiency of the main acceleration mechanism, and then the propagation of cosmic rays from AGNs to our Galaxy. The cosmic ray flux coming from all AGNs must be significantly less than the observed flux for energies below $10^{19}$ eV, since the latter is thought to be mostly Galactic (as is
explained in Chapter 2). Even though this constraint exists, we find that the cosmic ray luminosity at each AGN (for a flux from $10^9$ to $10^{19}$ eV) can still be between $10^{44}$ and $10^{46}$ ergs/s, without violating the observations. This work has been summarized in a recent publication (Crosas and Weisheit, 1993b).

We use this range of cosmic ray luminosities to perform the spallation calculation in Chapter 4. We assume that the cosmic rays are produced in the central source ($\sim 1$ pc), and diffuse out (with a diffusion coefficient that varies from $D \sim 10^{26}$ to $D \sim 10^{28}$ cm$^2$ s$^{-1}$), interacting with the surrounding gas distributed in a sphere of about 100 pc radius (NLR). The highest-energy cosmic rays ($E \sim 10^{19}$ eV) are destroyed in the center by photomeson and pair production, due to the large photon density. Cosmic rays with energies between $10^{16}$ eV and $10^{19}$ eV escape almost freely from that sphere, and probably from the entire host galaxy. Still lower-energy cosmic rays are the ones that spend more time ($10^5$ or $10^7$ years, for the large and the small diffusion coefficient respectively) in the NLR. They also are more efficient in producing light elements by spallation. The physical conditions of the gas, the cosmic-ray flux and the geometry and dimensions of the region of interest are very different from those of our present Galaxy. The NLR environment therefore provides new conditions for to the equations that describe the diffusion, the energy losses and the spallation of cosmic rays.

We obtain the Li, Be and B abundances in the NLR after the AGN phase (lifetime $T_{AGN} \sim 10^8$ years) for different cosmic ray flux models. We find that the production of these elements is not negligible under the AGN conditions. Therefore, in Chapter 5 and 6, we are able to compare these results with observed upper limits for the abundances of light elements in the NLR (specifically, the B abundance, since BIII has a line, $\lambda 2066\AA$, likely to be detected in AGN spectra). The upper limits found for the BIII line from AGN spectra can lead to upper limits for B abundance once the B ionization and excitation balance have been determined. For this calculation we considered Auger transitions, photoionizations, radiative and dielectronic recombina-
tions, collisional excitations between states, and radiative decays, and in fact had to compute rates for most of these processes.

In chapter 6, we explore some consequences of these (significant) amounts of cosmic rays on the chemistry of the dense, so-called "broad-line-region" clouds. Finally, we consider the possibility of our Galaxy having passed through an active phase. This would modify the Li, Be and B production through spallation reactions involving a cosmic ray flux larger, flatter, and probably more confined, than the flux in the present Galaxy. This scenario could help to explain some of the observed Galactic abundances.
Chapter 2

COSMIC RAYS

2.1 Observations

2.1.1 Detectors

Cosmic rays are nuclei with energies from a few MeV up to $10^{20}$ eV (and perhaps beyond). They are mainly protons and alpha particles. Cosmic rays with energies lower than $E \approx 10^{14}$ eV can be detected from the top of the atmosphere using balloons or spacecraft. Since the number of cosmic rays decreases with increasing energy, the area and the exposure time of the detectors need to be increased in order to obtain statistically significant data. The largest cosmic ray detector (which belonged to the University of Chicago and flew on the Spacelab) had an area of $\sim 2 \text{ m}^2$ and took data of $\geq 10^{14}$ eV cosmic rays, during approximately 90 hours.

Higher energy cosmic rays are very scarce and therefore very hard to detect directly. However, their secondary particles, which form through interactions with particles from the atmosphere, can be detected in large arrays ($\sim \text{ km}^2$) on the ground. At present, there exist four detectors of cosmic ray air showers operating in different parts of the world: Haverah Park (UK), Yakutsk (Russia), Fly's Eye (USA), Akeno (Japan). Their observations seem to agree well for the whole range of energies in which cosmic rays are observed, except the highest energies, $E > 10^{19}$ eV.

2.1.2 Spectrum

Figure 2.1 is a sketch of the differential cosmic ray energy spectrum $j(E) \ (\text{part/cm}^2 \ \text{sr s eV})$. The cosmic ray spectrum at low energies is thought to be well understood:
Figure 2.1  Observed cosmic ray flux, multiplied by energy squared, versus energy. The flux is fitted to 4 power-laws, \( j(E) = j_0 E^{-\alpha} \) (part/cm\(^2\) sr s eV), corresponding to 4 different energy intervals.
From about $10^{10}$ eV to $3 \times 10^{15}$ eV the spectrum is observed to be a power-law with a differential spectral index $\alpha = 2.6$. Particles in this energy range presumably are accelerated by shocks in Galactic supernova remnants. There is a feature at $3 \times 10^{15}$ eV known as the "knee" of the spectrum, where the slope steepens to $\alpha = 3$.

Recently, most of the attention has been put into cosmic rays of higher energies ($E > 3 \times 10^{15}$ eV), since there exist more discrepancies and uncertainties regarding their origin. The most recent data from the four detectors have revealed that the slope in the energy range from $3 \times 10^{15}$ to $4 \times 10^{17}$ eV is $\alpha = 3.02 \pm 0.02$, but at $4 \times 10^{17}$ eV it steepens even more, with a differential spectral index of $\alpha = 3.1 \pm 0.06$ (Haverah Park) or $\alpha = 3.24 \pm 0.18$ (Akeno). Beyond $10^{19}$ eV the spectrum flattens again, with $\alpha = 2.4 \pm 0.18$ (Haverah Park), $\alpha = 2.42 \pm 0.27$ (Fly's Eye) or $\alpha = 2.44 \pm 0.52$ (Akeno). At still higher energies there are significant differences among the four groups: Yakutsk reported a steepening of the spectrum at $4 \times 10^{19}$ eV and does not see events above $6.4 \times 10^{19}$ eV. However, Haverah Park has seen events even at $E > 10^{20}$ eV, and Fly's Eye and Akeno see that the power-law continues, at least up to $10^{20}$ eV (Watson, 1991; Efimov, 1991; Cooper et al, 1991; Ishima, 1991).

2.1.3 Composition

Cosmic ray abundances are best measured below $10^{15}$ eV. There, they are, in general, similar to solar abundances. The main difference is the large enhancement of light elements, Li, Be and B, and some heavy elements such as Sc, Ti, V, Cr and Mn. The light elements are formed through spallation reactions between primary cosmic rays and nuclei from the interstellar medium. The observed cosmic ray abundances are well understood by using propagation models of primary cosmic rays, with solar abundances, traversing the interstellar medium.

At very high energies, there is very little information about the mass composition of cosmic rays due to difficulties in the analysis. However, the four detectors agree on a main characteristic: at $10^{19}$ eV there is a change in the composition from mostly
protons to a mix including heavier nuclei (up to Fe). At high energies, even if the observations do not measure directly the cosmic ray composition, the data are consistent with models in which the proton component is 40% – 50% and the rest is mixed of heavier nuclei. More knowledge of the cosmic ray composition is needed in order to understand well the origins of these extremely energetic particles.

2.1.4 Anisotropy

Cosmic rays are not completely isotropic in their arrival directions. In the wide range of energies from $10^{12}$ to $10^{19}$ eV, there has been found a correlation between the anisotropy of the cosmic rays (represented by the amplitude of the first harmonic of the arrival directions of the air showers) and their energy spectrum (Hillas, 1984). The behavior of the anisotropy is the following: in the energy range from $10^{12}$ to $3 \times 10^{15}$ eV, the anisotropy increases very slightly with energy, or is practically independent of energy. At $E \geq 5 \times 10^{15}$ eV, the anisotropy amplitude starts to increase significantly as energy increases until $10^{19}$ eV, where there is a dramatic change and no more evidence of anisotropy is found.

Taken altogether, this behavior is consistent with a Galactic origin for particles with $E < 10^{19}$ eV. At $3 \times 10^{15}$ eV, “leaking” of cosmic rays from the Galaxy may start to be important, since particles are not completely trapped by the Galactic magnetic field anymore; this phenomenon is accentuated more at higher energies, so the trajectory of the particles becomes gradually less curved, until a certain energy for which most of the observed cosmic rays must come straight from the Galactic plane if they have a Galactic origin. This explains the increase of anisotropy with increasing energy. However, the extreme case of rectilinear trajectories would occur at $E \geq 10^{19}$ eV (the gyroradius of protons at this energy in a Galactic field of 1 µG is about 10 kpc), where, as it has been said, the anisotropy pattern changes. These data are interpreted to mean that such cosmic rays do not come from the Galactic plane, i.e., cosmic rays with $E \geq 10^{19}$ eV probably have an extragalactic origin.
2.2 Sources

2.2.1 Galactic Cosmic Rays

It is generally accepted that the acceleration of cosmic rays to energies $E \leq 3 \times 10^{15}$ eV occurs in shocks formed by supernova remnants expanding in the interstellar medium of our Galaxy, mainly because such a mechanism provides the desired power-law, omnidirectional distribution, and supernova energetics.

It is much harder to understand the acceleration of cosmic rays to higher energies, at least in the Galactic environment. It is thought that direct acceleration in pulsars can produce some particles with $E > 10^{15}$ eV (eg, Cygnus X-3), but it is not clear that this would give the observed power-law and, even if it would, particles likely could not be accelerated to energies of the order of $10^{18}$ eV. In spite of the lack of a convincing acceleration mechanism, it is still believed that the cosmic rays at this high energy range are Galactic; this additional conclusion is based on the anisotropy of arrival directions.

It has been mentioned above that the steepness of the spectrum at these energies can be explained by cosmic ray leakage from the Galaxy, but there exist other possibilities that still need to be explored in detail. One of them is that the accelerated particle spectrum at the cosmic ray sources is different for $E > 10^{15}$ eV, giving a steeper power-law. Another possibility is that there is a superposition of sources of different nature, with different spectra, and the sum of them gives the observed power-law. If so, the leakage of cosmic rays from the Galaxy may actually occur at higher energies, $E \approx 10^{17}$ eV, where further steepening is observed. (There is now a consensus view that this is what really happens, because it matches better the Galactic magnetic field model, but the picture has not been studied in detail yet.)
2.2.2 Extragalactic Cosmic Rays

There is a strong conviction that cosmic rays at $E > 10^{19}$ eV are extragalactic, since there are changes in the anisotropy, the spectrum and the composition, and mainly because the Galactic magnetic field does not contain them. At these ultra-high energies, we need to consider the interactions of the cosmic rays with the metagalactic radiation as they propagate through space. The metagalactic radiation at present is a microwave electromagnetic radiation in thermal equilibrium with a temperature of 2.7 K (COBE results). The interactions with this radiation will modify the original spectrum (at the source) through energy losses due to pair creation and photo-pion production, in addition to the changes produced by cosmological redshift. There have been several analytical calculations of the propagation of extragalactic cosmic rays that include these three effects (Hill and Schramm, 1985; Berenrsky and Grigor'eva, 1988), and more recently there has been a numerical calculation, using a Monte-Carlo method, that also includes the effects of the energy loss fluctuations from the evolution of background photons (Yoshida and Teshima, 1991).

Even though there are differences in these calculations, they all reach basically the same conclusions: several significant features appear in the cosmic ray spectrum due to the interactions with the metagalactic cosmic background radiation (CBR). First, a pair creation (Eq. 2.1) bump and dip at $E \approx 10^{18}$ eV and then, a pion production (Eq. 2.2) bump followed by a "black-body" cutoff.

\[
p + \gamma(CBR) \rightarrow p + e^+ + e^-
\]

(2.1)

\[
p + \gamma(CBR) \rightarrow p + \pi^0
\]

(2.2)

\[
\rightarrow \pi^+ + n
\]

(2.3)

The energy where the cutoff occurs decreases as the time of propagation of the cosmic rays increases (but it is usually in the energy range from $10^{19}$ to $10^{20}$ eV). The bumps are the result of conservation of particles (protons) when there exists a cutoff in the
spectrum. They are actually formed in the following way: after each interaction, the outgoing protons have less energy than the incoming ones, but not much less, because the energy loss drops exponentially with decrease of energy. Thus, all the resulting protons contribute to the cosmic ray flux at energies slightly lower than the threshold energy of the reactions. The “dip” is just a consequence of the bumps and the steepening of the spectrum. As the energy of the injected particles increases, the features become more pronounced.

However, for the case of many sources, since the features are adding incoherently, the pair creation bump and dip practically disappear, and the pion production bump is not very significant. So, for a universe filled with sources, there is not much observable structure, but the cutoff is still present and can be of great relevance. In fact, for a homogeneous metagalactic model in which cosmic rays propagate through the universe for about $10^{10}$ years, a cutoff at $3 \times 10^{19}$ eV would need to be seen, due to the interactions with the microwave background, i.e., the Zatsepin-Greisen cutoff (Zatsepin and Kuzmin, 1966; Greisen, 1966). Since recent data show that there is no cutoff at this energy, this model seems to be ruled out. This means that the extragalactic part of the spectrum is not due to cosmic rays from, e.g., high-redshift quasars. Indeed, there may not be even cosmic rays with $E > 10^{19}$ eV escaping from quasars, because they can be easily destroyed in the luminous central region of the quasar itself, through the same pair creation and photopion production processes. Consequently, to explain the observed cosmic ray spectrum for $E > 10^{19}$ eV, we need extragalactic sources that are not too distant from us and do not have as intense radiation fields to destroy the local cosmic rays. There are several suggestions that satisfy these characteristics, for instance, the Virgo supercluster and nearby radio-galaxies. These possibilities might be tested with more accurate anisotropy observations at ultra-high energies.

Even though quasars do not contribute to the high end of the observed cosmic ray spectrum, it is likely that they generate in their centers high-energy particles that
affect the local gas, due to their high activity and energy output (their radio and \( \gamma \) ray emission is supposedly associated with energetic electrons). At the same time, part of the high-energy particle flux in a certain energy range (maybe from \( 10^{17} \) to \( 10^{19} \) eV) can escape, and propagate almost without interacting with the microwave background radiation, because their energy is sufficiently low. The sum of all the fluxes from quasars (and other active galaxies) would contribute to the observed spectrum in the corresponding range of energies. Thus, the observed cosmic ray flux in this energy range provides an upper limit to the flux of high-energy particles interacting with the gas in, and escaping from, active galaxies (see Chapter 3, Section 5).

2.3 Summary of Acceleration Mechanisms

The best studied acceleration mechanism for cosmic rays is shock acceleration. This acceleration is understood in terms of the so-called first-order Fermi mechanism, which can typically accelerate particles up to energies of about \( 10^{14} \)–\( 10^{15} \) eV, and reproduce a power-law spectrum. Such a mechanism works in the following way: particles near a shock front are scattered repeatedly by Alfven waves. The latter can be considered as stationary magnetic fluctuations, since their speed is very low compared with that of the flow. After several scattering events, the particles change their directions and may cross the shock front. This means that the particles move into a new medium that is moving with a different velocity, related to that of the previous one by the compression ratio \( \frac{r}{u_1} = \frac{u_1}{u_2} \), with \( u_1 \) being the upstream velocity and \( u_2 \) the downstream velocity. Particles thereby are Doppler shifted in energy. The average gain of energy is linearly proportional to the velocity of the medium. (The linearity is the reason why it is called first-order Fermi acceleration.)
For relativistic particles, the particle energy distribution function $dN(E)$ produced by shock acceleration is fixed by the compression ratio $r$,

$$dN(E) \propto E^{-\alpha} \quad \alpha = (r + 2)/(r - 1) \quad .$$

(2.4)

For strong shocks, $r=4$ and the spectral index $\alpha = 2$, which is close to the observed value.

Two different methods have been applied to actually calculate this spectrum, and both yield this same result. The first method is based on a microscopic approach, in which the spectrum is obtained by calculating the probability of crossing the shock a certain amount of times and the energy gain every time the shock is crossed (Bell, 1978). The second method is based on a macroscopic approach, and involves solving the diffusion equation on each side of the shock. Then, the spectrum can be obtained by matching the particle flux across the shock front and specifying the flux far from the shock (Blandford and Ostriker, 1978). (Further explanation of these methods/schemes can be found in Appendix A).

There exist more detailed studies, which include particle energy loss by radiation processes, escape of particles in the downstream region, and a nonlinear modification of shock structure due to the back-reaction of the accelerated particles, but the basic result does not change much.

The main shocks that can accelerate the bulk of Galactic cosmic rays are those found in supernova remnants. It is possible that other type of shocks, for instance, termination shocks of the Galactic wind, could accelerate particles to higher energies. Shocks in active galaxies will be discussed in the next chapter.

The other mechanism that Fermi originally studied is a second-order acceleration process. In this case, the particles bounce back and forth between moving clouds which act as magnetic mirrors. Particles can either gain or loose energy when they encounter a cloud. Thus, the mechanism is less efficient than the first-order Fermi,
and for that reason, is not usually considered to explain the acceleration of Galactic cosmic rays.

There are other acceleration mechanisms for Galactic cosmic rays that have not been as well accepted as shock acceleration. One of them is direct acceleration in compact sources, namely, near neutron stars. For example, the rotational energy of the neutron star might be converted somehow to particle acceleration, or, in a binary system, the gravitational energy of the accreted material might be also used to accelerate particles. However, these mechanisms appear very unlikely to reproduce the observed cosmic ray power-law spectrum.

The above brief review of cosmic rays within the Galaxy will be useful when we explore the likely cosmic ray luminosity in and around active galactic nuclei.
Chapter 3

AGNs AS COSMIC RAY SOURCES

3.1 Overview of Active Galactic Nuclei (AGNs)

Quasars, Seyfert galaxies, radio galaxies, Liners, BLac and OVV objects are known to be manifestations of galaxy "activity" (Osterbrock, 1991). They are different from normal galaxies because their luminosities are greater ($L \approx 10^{41} - 10^{48}$ ergs/s), and they emit nonstellar continuum radiation. Their active region has been found to coincide with the optical center of the galaxy. They are therefore commonly referred to as Active Galactic Nuclei (AGNs).

Quasars are the most luminous of these objects. They are similar to Seyfert Type 1 galaxies in that they show broad permitted emission lines (with a width of $\sim 5000$ km/s) and narrow permitted and forbidden lines (with a width of $\sim 500$ km/s). Contrarily, Seyfert Type 2 galaxies do not show broad emission lines. Radio galaxies are associated with strong radio emission, and they usually show two oppositely directed radio jets (several quasars show the same jet structure). Some radio galaxies present broad emission lines (like Seyferts 1) and some narrow emission lines (like Seyferts 2). Liners are the least luminous AGNs. They show very narrow emission lines originated in low ionization regions. Finally, BLac and OVV (optical violent variables), which are usually called Blazars, do not show any emission lines. All these AGNs are also classified into two big groups: radio loud and radio quiet. There are only about 20% radio loud AGNs, and the rest are radio quiet.

A standard model for AGNs has been gradually improved to try to match all observations since AGNs were discovered (Netzer, 1992; Blandford and Rees, 1992;
Blandford et al, 1990). This model describes the active nucleus as a massive black hole \((M \approx 10^6 - 10^9 \, M_\odot)\) surrounded by an accretion disk. The source of luminosity is conversion of the gravitational energy released by matter falling into the black hole located at the center. The temperature of the accretion disk itself can be responsible for the optical and the ultraviolet continuum. Part of the X-ray continuum can also be explained by using the accretion disk, if the disk satisfies certain properties, e.g., for a geometrically and optically thin disk. But the hard X-rays are more difficult to explain; they could come from a very hot optically thin inner disk, corona or jets. The infrared continuum may be thermal and originate from heated dust. The whole continuum spectrum is usually described with two or three different power-laws, in which the differential spectral index varies from \(\alpha = 0.5\) to \(\alpha = 2\). In the radio energy range, however, the spectrum can be even flatter than \(\alpha = 0.5\) when the flux is associated with the compact region. But, the radio flux associated with a more extended region is usually steeper than \(\alpha = 0.5\). Recently, there also have been successful \(\gamma\) ray observations using the Compton Gamma Ray Observatory (C.G.R.O.). These observations reveal the presence of very high-energy continuum radiation for many radio loud quasars, which can be fitted again to a power-law.

The region where the broad lines are emitted is at about 1 pc from the central source and consists of small clouds, which move rapidly in different directions. The temperature and density of these clouds are \(T \approx 10^4 \, K\) and \(n \approx 10^9 - 10^{10} \, cm^{-3}\). The narrow line region is the most extended region of the AGN and is located at about 100 pc (up to 1000 pc). It is also formed by clouds or filaments with almost the same temperature but lower density, \(n \approx 10^4 \, cm^{-3}\). The continuum radiation coming from the nucleus, mainly the X-rays, is reprocessed in these clouds giving rise to the observed broad and narrow lines (Weisheit, Shields and Tarter, 1981; Kwan and Krolik, 1981). The clouds may be confined by the magnetic field and/or a hot, tenuous gas.
As an elaboration of this standard model, a unified theory has been suggested (e.g., Barthel, 1989; Kinney, 1994): all the different AGNs are essentially the same type of object seen from different lines of sight. This can be possible if a molecular torus is surrounding, and in some cases obscuring, the central region (Krolik and Begelman, 1988). This idea has been more accepted since scattered broad lines were detected in Seyferts 2 (Antonucci and Miller, 1985; Miller and Goodrich, 1990).

In an effort to avoid the (controversial) massive black hole, other AGN models have recently been proposed. The model that has received most attention suggests and manages to show that a high concentration of supernovae in the center of these active galaxies can also reproduce quite well their observed continuum and line spectra (Terlevich and Melnick, 1985). Even if this model could explain some of the AGNs, it would have serious difficulties accounting for the radio jets from radio galaxies and some quasars. Furthermore, recent observations (Filippenko et al, 1993) do not support this so-called starburst model for the following reason: there is no evidence of absorption lines from hot stars in the spectrum of the AGN NGC 4395.

This is but a brief summary of what has been done so far in the study of active galaxies, considering mainly their continuum and line spectra. In the rest of this chapter we will concentrate on a different aspect of an AGN environment: the cosmic rays originating in their nucleus.

3.2 Particle Acceleration in AGNs

Acceleration of particles in AGNs can occur around the central black hole, in the accretion disk, and in the radio jets (see Figure 3.1). For radio quiet AGNs, the accretion disk is likely to be the most relevant site of this acceleration, and for radio loud AGNs, the radio jets may play a more important role. Furthermore, the acceleration of particles in the three regions may be related to each other. Here follows a discussion of the possible acceleration mechanisms in AGNs:
Figure 3.1 Particle acceleration regions in AGNs.
Particle acceleration near the black hole itself can occur if the black hole is rotating (Kerr black hole), which leads to the formation of a so-called ergosphere. The ergosphere lies between the space-like radius and the outside horizon of the black hole. Such acceleration arises when infalling material enters this region and separates into different parts, and one part falls into the black hole, with negative energy, and the other part escapes, with an energy larger than the initial one, since the total energy must be conserved (Penrose process). However, this process seems to be very impractical (Shapiro and Teukolsky, 1983; Bardeen, Press and Teukolsky, 1972), so its importance in an AGN environment is unlikely. Other acceleration processes around a black hole have not been explored in detail yet (more interesting results can be obtained when the black hole magnetic field is also considered).

A much more studied subject is the acceleration of particles by strong shocks (e.g., Blandford and Eichler, 1987), which can be formed in AGNs when material from the accretion disk moves rapidly towards and/or out from the black hole (Protheroe and Kazanas, 1983; Kazanas and Ellison, 1986). In the same way, if jets are present in the AGN, the energetic flow at large distances from the center also can form strong (hot spots) and weak (bow) shocks when it interacts with intergalactic material (Blandford and Netzer, 1990), accelerating particles once again. The way that particles can be accelerated in these shocks is by first-order Fermi mechanism, which was discussed in the Chapter 2 for Galactic shocks in supernova remnants (and a detailed description is given in Appendix A). In addition, in an AGN environment the shock itself can be relativistic, since outflowing, and sometimes infalling, material reaches very high velocities at regions near the massive black hole. Particle acceleration in relativistic shocks has been studied recently and interesting results have been obtained. To understand the differences between relativistic and nonrelativistic shock acceleration theory, we need to point out, first, that the methods applied to Galactic supernova remnants (see Chapter 2, Section 3) obtain the particle spectrum by assuming that the scattering of the relativistic particles keeps the particle distribution isotropic.
This means that the diffusion coefficient has spatial, but not angular, dependence, a situation that greatly simplifies the transport equation. However, when the flow moves relativistically, the distribution of particles cannot be considered isotropic anymore, so the transport equation depends on details of diffusion and can be very difficult to solve.

Some studies have been made following the microscopic approach (Peacock, 1981), but too many assumptions (Ellison and Reynolds, 1991) need to be made on the angular distribution of particles that cross the shock. Another approach is, again, a macroscopic one (Kirk and Schneider, 1987). In this case, the particle distribution is expanded in Legendre polynomials, which characterize the degree of anisotropy. The equation can be written in the form of eigenfunctions and eigenvalues, and be solved in the same way as radiation transfer equations are solved. The results provided by these relativistic studies show that the slope of the spectrum is always flatter than the nonrelativistic one, for a given compression ratio.

Other studies, that consider only values of the compression ratio that are consistent with the upstream velocity (Heavens and Drury, 1988), lead to a more complex result: when the upstream velocity is of the order of 0.1c, the thermal electrons in the medium will start to become relativistic and the specific heat of this medium will decrease from 5/3 to almost 4/3. This makes the compression ratio first increase with increasing upstream velocity. But, when the upstream velocity becomes highly relativistic, the effect is the opposite, and the compression ratio decreases to 5/2. This means that the spectral index may decrease from 2 to 1.7, for strong relativistic shocks, but then it increases again up to approximately 2.

From all these studies, it is clear that the compression ratio in strong relativistic shocks cannot be expressed anymore as \( r = (\Gamma + 1)/(\Gamma - 1) \), where \( \Gamma \) is the ratio of specific heats, as it is in strong nonrelativistic shocks. The relativistic expression for \( r \) must be obtained from the relativistic equations for momentum, energy and particle number conservation (across the shock front). Therefore, \( r \) depends on the specific
heats of the medium and the sound speed, which themselves depend on the velocity of the medium. For the extreme case in which the upstream velocity $u_1$ is very close to $c$, the relation between $u_1$ and $u_2$ is $u_1 u_2 = 1/3$, and the lowest value for $r$ is 2.43. For intermediate cases, $r$ must be determined numerically, after specifying the kind of medium in the shock region. More recent work uses Monte Carlo simulations to study relativistic shocks (Ellison et al., 1990). Their results are in good agreement with those obtained from analytical studies.

The most important conclusions from all these relativistic studies are the following: (i) The slope of the particle spectrum depends on the upstream velocity, the compression ratio, and the details of the scattering. (ii) The compression ratio changes as the upstream velocity increases toward $c$, reaching a maximum at about 0.5$c$. (iii) For a given $r$, the slope is always flatter in the relativistic case.

At lower energies ($E \leq m_p c^2 \sim 1$ GeV) the distribution function $dN(E)$ departs from the single power-law from of Eq. (2.4), but its actual shape depends on details of the particle diffusion near the shock front itself (Blandford and Eichler, 1987). Eventually, of course, $dN(E)$ must connect smoothly with the distribution of thermal particles.

Besides stochastic acceleration mechanisms, such as first-order Fermi acceleration, there are other ways that particles can be accelerated in an AGN environment. It has been proposed recently that, in hot spots of radio lobes, particles may be accelerated by a ‘shock-drift’ acceleration mechanism (Begelman and Kirk, 1990; Kirk and Heavens, 1989). In this mechanism, a particle gains energy as its gyrocenter crosses the shock front from upstream to downstream, by drifting parallel to the electric field. This mechanism is more efficient than first-order Fermi when the shock is highly oblique, i.e., when the upstream flow is relativistic and the magnetic field is parallel to the shock front (as in the case of superluminal shocks). In contrast, diffusive acceleration (first-order Fermi) is efficient when the magnetic field is aligned with the flow. There seems to be observational evidence that at least some hot spots are
produced by highly oblique shocks (Laing, 1982; Lonsdale and Barthel, 1984, 1986); in a few cases, there is deflection of the jet as it passes through a hot spot, and the downstream flow is also relativistic, (this can happen in highly oblique shocks). It is also observed that hot spots are associated with regions with higher synchrotron emission (Meisenheimer and Roser, 1986; Fraix-Burnet et al., 1989). Earlier studies tried to explain this characteristic in terms of adiabatic compression in the downstream flow, but 'shock-drift' acceleration provides a more efficient mechanism to accelerate electrons and produce larger amounts of synchrotron radiation in these regions. However, this acceleration is mainly important for radio galaxies, which always show these radio lobes with hot spots. In quasars and Seyferts type 1 galaxies, even if radio jets also exist, the first order Fermi acceleration is more likely to dominate there, since most of their jets are not superluminal.

It has recently been suggested that yet another acceleration mechanism can be important in an AGN environment (Haswell, Tajima and Sakai, 1992). This is direct acceleration by the electromagnetic field associated with the accretion disk. Since the disk is rotating, and the field and the plasma are coupled, the magnetic field wraps up tightly, causing a buildup of magnetic energy. They show that, in the regions where this occurs, explosive solutions (growing very rapid with time) for the electromagnetic fields are obtained in a magnetohydrodynamic (MHD) model. Then, if particles decouple from the MHD flow, they can be accelerated away from the edge of the disk to very high-energies, higher than $10^{20}$ eV. This model has not been re-investigated, and it is not clear yet that can actually work in an AGN environment.

The different acceleration mechanisms in AGNs described above are summarized in Table 3.1 (and their sites were illustrated in Figure 3.1). From this discussion we conclude that particles are likely to be accelerated in the central region of AGNs by strong, and sometimes relativistic, shocks, since acceleration mechanisms associated with the black hole are not efficient. The highest-energy particles might be accelerated by other mechanisms associated with the magnetic field in outer parts of the accretion
<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Characteristics</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Order Fermi (1)</strong></td>
<td>Efficient when magnetic field is perpendicular to the shock.</td>
<td>In shocks formed by infalling or ejected material, in the inner part of the accretion region.</td>
</tr>
<tr>
<td>Particle gains energy recrossing a shock front by scattering with magnetic turbulence near the shock.</td>
<td><strong>The spectrum of accelerated particles is dN(E) \propto E^{-2}, for strong shocks. The spectrum can be flatter for relativistic shocks.</strong></td>
<td>In shocks formed in radio jets, due to the interaction with the intergalactic medium.</td>
</tr>
<tr>
<td><strong>Shock-Drift (2)</strong></td>
<td>Efficient when magnetic field is practically parallel to the shock.</td>
<td>In oblique shocks formed by superluminal flows, which are associated with the hot spots in radio lobes (mostly in radio galaxies).</td>
</tr>
<tr>
<td>Particle gains energy as its gyroradius crosses a shock front, by drifting parallel to the electric field.</td>
<td><strong>Acceleration to very high energies:</strong> $10^{18} \leq E \leq 10^{20}$ eV.</td>
<td></td>
</tr>
<tr>
<td><strong>Direct Acceleration (3)</strong></td>
<td>Acceleration to energies around $10^{20}$ eV.</td>
<td>In the edge of the accretion disk (near the corona), where the density is lower and particles can escape away from the disk.</td>
</tr>
<tr>
<td>Particle is accelerated by the electromagnetic field of the accretion disk, in regions where the magnetic energy has built up due to both rotation of the disk and coupling of the field with the plasma.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Penrose Process (4)</strong></td>
<td>Very unlikely. Probably not important in an AGN environment.</td>
<td>Near the black hole.</td>
</tr>
<tr>
<td>Particle gains energy falling in the ergosphere of a rotating black hole, and splitting in two, in such a way that one piece goes down to the black hole (with negative energy) and the other piece escapes with larger energy than initially.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.1** Acceleration mechanisms in AGNs
*(see text for explanation and references)*.
disk, but the corresponding models still need to be revised. The particles may escape from the inner region through a jet, and then diffuse out from it, or through other processes that will be discussed in the next section. Furthermore, particles may be accelerated in the jet through shock-drift or Fermi acceleration in shocks far away from the nucleus.

Thus, the following characteristics, derived from this acceleration mechanisms discussion, can be outlined: (i) First-order Fermi acceleration is still the most relevant mechanism in the AGN environment, at least for cosmic rays with $E \leq 10^{19}$ eV. (ii) The energy spectrum of accelerated particles has a slope near $\alpha = 2$ if the shocks are non-relativistic. This slope is flatter ($\alpha = 1.7-1.9$) for mildly relativistic shocks ($u_1/c \approx 0.5$), which are likely to be formed in AGN environment. (iii) Non-relativistic particles ($E \leq 1$ GeV) also are likely to have a distribution with $\alpha < 2$ (Ellison and Eichler, 1984)

It is therefore reasonable to use a power-law with spectral index $\alpha$ varying between 1.7 to 2.3 in our calculations, in order to describe the cosmic ray flux originating in AGNs.

3.3 Efficiency of Cosmic Ray Acceleration

Besides estimating a range of possible power-laws, we are also interested in estimating a range of cosmic ray luminosities for AGNs. This range will be useful in order to set initial values in our AGN spallation calculation, presented in the next chapter.

A first attempt to estimate a cosmic ray luminosity range in AGNs can be based on relating the unknown cosmic ray luminosity with the known radiation luminosity of the object. One would expect that an object with a large energy output in radiation will also have a large output in energetic particles. The proportionality between energy output in radiation and in particles might not be the same for different objects. However, if the mechanism to accelerate the particles is the same for these different objects, then their efficiency of converting energy of the system into kinetic energy
of the accelerated particles is likely to be similar. In the case of Galactic shock acceleration, it is known that 5 – 10% of the total energy in the shock is converted to cosmic ray energy (Blandford and Eichler, 1987). Thus, if cosmic ray acceleration in the central region of an AGN is also given mainly by shocks (see previous section), its efficiency is likely to be about the same as that in Galactic shock acceleration. The energy available in the inner region of the AGN can come from the following processes: (i) Electromagnetic extraction of black hole rotational energy (Blandford and Znajeck, 1977):

\[ L_{\text{em}} \approx 10^{45} M_8^2 \left( \frac{a}{m} \right) B_4^2 \text{ ergs s}^{-1}, \]  

where \( a \) is the angular momentum, \( m = GM/c^2 \), \( M_8 \) is the black hole mass in \( 10^8 M_\odot \) units, and \( B_4 \) is the magnetic field near the black hole in \( 10^4 \) G units. (ii) Gravitational energy of accreting gas:

\[ L_{\text{acrr}} \approx L_E \approx 3 \times 10^{46} M_8 \text{ ergs s}^{-1}, \]

where \( L_E \) is the Eddington luminosity. If we consider typical AGN values \((M_8 = 1, B_4 = 1, a/m = 1)\), and assume first that most of the energy from (i) goes to shocks, then we obtain an upper limit for cosmic ray production of about \( 10^{44} \) erg s\(^{-1}\). If we use the energy from (ii), we obtain \( L_{CR} \approx 10^{45} \) erg s\(^{-1}\). However, it is likely that most of the accretion luminosity appears as radiation. The electromagnetic luminosity is probably contributing mainly to acceleration of particles (but a large fraction might go into the energetic electrons, instead of protons). If the mass of the black hole is greater, e.g. \( 10^{10} M_\odot \), then the cosmic ray luminosity can reach larger values, up to about \( 10^{46} \) ergs s\(^{-1}\).

However, recent studies on X-ray and radio luminosity of radio-loud AGNs (Bechtold, 1993) suggest that as much as 99% of the power extracted from the spin of the black hole goes into kinetic energy of the particles. This astonishing result might not apply to radio-quiet AGNs, for which the value cannot be obtained directly since there is
no significant radio luminosity observed. Therefore, other indirect arguments should also be used to set upper limits to the cosmic ray luminosity in these type of AGNs.

3.4 Relation between Cosmic Rays and Gamma Rays from AGNs

Gamma ray observations have always been closely related to cosmic ray studies, because they can be used to identify regions where energetic particles interact with matter or radiation. The main mechanisms that can produce $\gamma$ rays are (i) collisions between cosmic ray protons and other protons or photons, which first form $\pi^0$ or $e^+e^-$ pairs, and then decay or annihilate to form $\gamma$ rays, (ii) bremsstrahlung of cosmic ray electrons, (iii) inverse Compton scattering of lower-energy radiation, and (iv) synchrotron radiation. In our Galaxy, (i) and (ii) are the dominant sources of the observed diffuse $\gamma$ rays (above 10 MeV). Recent $\gamma$ ray observations of AGNs suggest that the sources of high-energy radiation in some of these objects might be very different from those of our Galaxy.

The highest-energy (20 MeV to 30 GeV) instrument in the Compton Gamma Ray Observatory (CGRO), EGRET, has been very successful in the search for $\gamma$ ray - emitting AGNs (Fichtel et al, 1992). It has detected so far 23 AGNs, which show, in general, a power-law that extends to the highest observable energy. Most of these AGNs present characteristics typical of blazars, which are thought to be AGNs with radio jets pointing towards the Earth. The observed blazars are not necessarily the closest ones to our Galaxy. It is found that their average $\gamma$ ray luminosity is between $10^{45}$ and $10^{46}$ ergs/s if their radiation is beamed (but $10^{48}$ ergs s$^{-1}$ if it is emitted isotropically). Their spectral index in the photon power-law is between $\alpha = 1.7$ and $\alpha = 2.4$. These observations seem to indicate that $\gamma$ ray emission has the dominant energy output in this type of AGNs. EGRET, however, has failed to detect $\gamma$ radiation from Seyfert galaxies and some of the closest blazars. COMPTEL and
OSSE, which are the instruments in the CGRO sensitive to lower-energy $\gamma$ rays, have detected fewer AGNs (Collman et al., 1992). A combination of the EGRET results with the COMPTEL and OSSE results (either detections or upper limits) suggests that Seyferts may present a break at about 100 KeV, i.e., the power-law from few KeV up to 100 MeV becomes steeper for these AGNs, so the flux is not very large at these high energies (Schachter and Elvis, 1993).

These two well distinguished $\gamma$ ray emission properties corresponding to two types of AGNs seem to be correlated with the radio properties. The first group are mainly radio-loud AGNs and the second group are radio-quiet AGNs. The association of radio-loud AGNs, like blazars, with radio jets suggests that the jets are also responsible for the high-energy $\gamma$ ray emission observed from these AGNs. A lot of attention has been given to this idea (e.g., Sikora, Begelman and Rees, 1992; Dermer and Shlickeiser, 1993). The most recent and attractive picture, investigated by Dermer and Shlickeiser (1993), proposes that $\gamma$ rays are produced through inverse Compton scattering of accretion disk photons by jet electrons.

However, we are actually more interested in the energetic particles diffusing through in the AGN emission region than those confined in a radio jet: In our study, we consider the possibility of large fluxes of cosmic rays in the narrow line region of AGNs (see Chapter 4). Evidently, in this scenario the cosmic ray protons, besides undergoing spallation reactions, will interact with the protons from the NLR gas. If the cosmic ray protons have large enough energies, these interactions will produce $\gamma$ rays above 70 MeV. In order to find if this $\gamma$ ray production is detectable, we can calculate the amount of $\gamma$ rays produced in the NLR and compare with the sensitivity of the detectors. For example, if we consider a cosmic ray power-law $F(E)$ (in particles cm$^{-2}$ s$^{-1}$ eV$^{-1}$), with differential spectral index $\alpha = 2$, and cosmic ray luminosity of $10^{45}$ ergs s$^{-1}$, from $10^9$ to $10^{19}$ eV, then the density of $\gamma$ rays produced per unit time
and energy can be obtained from (Gaisser, 1990):

$$q_\gamma(E) = 4\pi \frac{\rho}{m_H} (\sigma_{pp}^{inel} \frac{2Z_{N-\pi^0}}{\alpha}) F(E).$$  \hspace{1cm} (3.3)

Here, \(\rho/m_H = 10^4 \text{ cm}^{-3}\) is the particle density in the region of interest (narrow line region clouds), \(\sigma_{pp}^{inel} = 30 \text{ mb}\) is the cross section for proton-proton interaction close to threshold (E\(\sim\) 10 GeV), and \(Z_{N-\pi^0}\) represents the average fraction of the interaction energy that goes to \(\pi^0\), which is approximately 0.5 (Gaisser, 1990). Substituting all these values into Eq. 3.3, we find that \(q_\gamma \approx 5 \times 10^{-26} \text{ cm}^{-3} \text{ s}^{-1} \text{ eV}^{-1}\). This is only the value at threshold, which corresponds to \(\gamma\) rays with energies around \(E = m_\pi/2 = 10\text{ MeV}\). This is the photon energy in the pion rest frame, and there is a symmetric distribution with respect to this value, since the decay \(\pi^0 \rightarrow \gamma\gamma\) is isotropic in the pion rest frame (Stecker, 1971). Pions with some kinetic energy will produce \(\gamma\) rays with larger energies, resulting in a photon power-law with \(\alpha\) equal to that of the injected cosmic ray spectrum. If we consider that the \(\gamma\) rays are produced over all the NLR volume and assume that the source is about 100 Mpc from the Earth, we find that the \(\gamma\) ray flux received at Earth is between 6 and 8 orders of magnitude smaller that the detectors sensibility (which is \(\sim 10^{-10}\text{ cm}^{-2}\text{s}^{-1}\text{eV}^{-1}\) at 1 MeV, and \(\sim 10^{-17}\text{ cm}^{-2}\text{s}^{-1}\text{ eV}^{-1}\) at 1 GeV).

Besides proton-proton interactions, proton-photon interactions can also produce \(\gamma\) rays in the central region. In fact, high-energy protons will encounter large amounts of ionizing radiation in the inner region of the AGN, before interacting with the NLR gas. Protons with \(E \geq 10^{12}\text{ eV}\) can produce pairs by interacting with soft X-rays (1 KeV), and the pairs annihilate after loosing their energy. The cross section at threshold is about \(10^{-26}\text{ cm}^{2}\) (Dermer, 1984). Using the density of photons and protons and the value of the cross section, we estimate the \(\gamma\) ray production through this process. We find that the flux received at Earth is again not detectable by several orders of magnitude. In addition, protons with \(E \geq 10^{15}\text{ eV}\) can produce neutral pions by also interacting with X-rays. In this case, the cross section at threshold is \(\sim 10^{-28}\text{ cm}^{2}\)
(Dermer, 1984). Estimating the flux of $\gamma$ rays produced through this process, we find one more time that the flux is much lower than the sensitivity of EGRET.

Therefore, cosmic ray luminosities in the center of AGNs of about $10^{45}$ ergs s$^{-1}$, and even $10^{46}$ ergs s$^{-1}$, do not contradict recent $\gamma$ rays observations of AGNs.

3.5 Propagation of Cosmic Rays from AGNs to Earth

3.5.1 Sum of Cosmic Ray Fluxes Escaping from AGNs

Another argument that can be used to place approximate upper limits on the cosmic ray luminosity in AGNs is based on the observed cosmic ray spectrum. Since cosmic rays from AGNs are unlikely to contribute to the observed spectrum (see Chapter 2), we can use the observed values to set upper limits, by computing the propagation of cosmic rays from AGNs to Earth.

In order to calculate the propagation of cosmic rays emanating from AGNs, we can consider a thin shell of large radius, with sources distributed in it, from which cosmic rays are emitted and propagate rectilinearly towards the observer located in the center. In this picture, we get a flux from every volume element, and then integrate it from the center to some outer radius of the sphere, $R_0$. We consider a flat universe, as is predicted by inflationary models. For this case $R(t) dr=cdt$, and then $R_0=c/H_0$, where $H_0$ is the present value of the Hubble constant (Weinberg, 1972). It is convenient to express everything in terms of cosmological redshift, and then the integration is with respect to redshift instead of radius. We assume AGN cosmological evolution, given by

$$n(z)L(z) = (1+z)^{3+m}n_0L_0$$  \hspace{1cm} (3.4)

where $n$ is the density of sources, $L$ their luminosity, the subscript "o" on $n$ and $L$ denotes the present epoch, and the parameter $m$ is different from zero if there is luminosity evolution. We also assume that each source emits cosmic rays in the form
of a power-law:

$$\phi(E, z) = k E^{-\gamma-1} \left( \frac{\text{particles}}{\text{eV s}} \right)$$  \hspace{1cm} (3.5)

where $E_s$ is the energy at the source, $k$ is a constant, and $\gamma$ is the integral spectral index ($\alpha = \gamma + 1$ is the differential one). Then, we derive the following expression for the flux received by the observer from sources ranging out to redshift $z_{\text{max}}$ (Berezinsky and Grigor'eva, 1988):

$$j(E) = \frac{3}{8\pi} n_0 R_0 \phi(E) \int_0^{z_{\text{max}}} dz \frac{(1+z)^m}{(1+z)^{5/2}} \left( \frac{E_s}{E} \right)^{-\gamma-1} \frac{d E_s}{d E} \left( \frac{\text{particles}}{\text{cm}^2 \text{sr s eV}} \right)$$  \hspace{1cm} (3.6)

If no interactions with the microwave background radiation are taken into account, then the ratio between $E_s$ and $E$ depends only on redshift, and the previous expression simplifies to:

$$j(E) = \frac{3}{8\pi} n_0 R_0 \phi(E) \int_0^{z_{\text{max}}} dz \frac{1}{(1+z)^{5/2+\gamma-m}}$$  \hspace{1cm} (3.7)

In the case that interactions are considered, the ratio between $E_s$ and $E$ depends not only on $z$, but also on $E$ (and other parameters that describe the interaction). This additional energy-dependent term will lead to the formation of the features in the spectrum mentioned in the previous chapter (bumps, dip and cut-off).

The equation shown above is for the case where there is a minimum energy cutoff. However, in our calculation we use a AGN flux with not only a minimum, but also a maximum energy cutoff. The reasons why we introduce a minimum and a maximum energy in the AGN flux are the following: A minimum energy corresponds to the least energetic particles that can escape from the AGN. A maximum energy exists due to the interactions between the relativistic particles and protons and photons located in the nuclear region of the quasar. The existence of a maximum energy cutoff changes slightly Eq. 3.7; the slope of the flux received is modified in the range of energies from $E_{\text{max}}/(1+z)^2$ to $E_{\text{max}}$ (Hill and Schlamm, 1986). So, if we consider a power-law spectrum at the source such that

$$\phi(E) = K (E_0/E)^\alpha \quad E_{\text{min}} < E < E_{\text{max}}$$  \hspace{1cm} (3.8)
then the flux received at Earth is

\[ j(E) = \frac{3}{8\pi n_0 R_0 K'} \left( \frac{E_0}{E} \right) \alpha \frac{1}{m - \alpha - 1/2} \left[ (1 + z_{\text{max}})^{m-\alpha-1/2} - 1 \right] \quad (3.9) \]

for \( E < E_{\text{max}}/(1 + z)^2 \), and

\[ j(E) = \frac{3}{8\pi n_0 R_0 K'} \left( \frac{E_0}{E} \right) \alpha \frac{1}{m - \alpha - 1/2} \left[ \left( \frac{E_{\text{max}}}{E} \right)^{m/2-\alpha/2-1/4} - 1 \right] \quad (3.10) \]

for \( E_{\text{max}}/(1 + z)^2 < E < E_{\text{max}} \). This variation in the slope is due to the superposition of power-laws at different redshifts. It affects energies \( E > E_{\text{max}}/(1 + z)^2 \) because, on one hand, the maximum energy is decreased by \((1+z)\) as the flux propagates towards us. On the other hand, the observed energy, \( E \), is increased by \((1+z)\), when the flux is integrated from the source to the earth.

### 3.5.2 Parameters Used in the Calculation

The minimum energy is obtained from the strength of the magnetic field and the size of the AGN. For a certain energy, the gyroradius of the relativistic particles is larger than the size of the central region of the AGN. Then, the particle can easily escape to the intergalactic medium. The magnetic field in AGNs is not well known; the best estimates come from radio data, and the typical values are between \(10^{-5}\) and \(10^{-3}\) G. We take the lowest value to obtain a lower limit for the minimum energy. We also take a conservative value for the size of the AGN central region, 10 pc. Then, we use the relation between gyroradius and particle energy,

\[ eB_{\text{rg}} = \gamma m_p c^2 = E \quad (3.11) \]

We rewrite this equation in convenient units, and solve for the particle energy, substituting the values:

\( \left( \frac{E}{10^{17}\text{eV}} \right) = 0.92 \left( \frac{B}{1\mu\text{G}} \right) \left( \frac{r_{\text{rg}}}{1\text{pc}} \right) \Rightarrow E_{\text{min}} = 10^{17}\text{eV} \quad (3.12) \)

We estimate a maximum energy from the results of studies involving interactions between cosmic rays and photons and protons. Early studies in this field (Kazanas
and Ellison, 1986) show that primary protons with high enough energies \( (E \geq 10^{18} \text{ eV}) \), accelerated by first order Fermi mechanism, collide with other protons from the central region of the AGN, and form electron-positron pairs. This is a good way to produce large amounts of relativistic electrons, since those produced by Fermi acceleration do not exist very long due to radiation losses. It is different for protons, which do not suffer radiation losses as severe as electrons. However, a large fraction of high-energy primary protons are destroyed by the proton-proton collisions, unless they escape easily from the shock region through jets, at least in the case of radio loud AGNs.

Other studies (Sikora et al., 1987) claim that not only proton-proton, but also proton-photon collisions are important. At \( E > 10^{15} \text{ eV} \), they are even more efficient at producing relativistic electrons than the collisions involving only protons (since those convert a large fraction to neutrinos). These studies show that the maximum energy that protons can achieve without being destroyed is around \( 10^{18} \text{ eV} \).

More recent papers (Sikora et al., 1989) are focused on the large amount of neutrons produced in these proton-proton and proton-photon collisions. These neutrons escape from the central region (since they are not magnetically coupled to the plasma), but decay at distances less than 100 pc from the source (Begelman, de Kool and Sikora, 1991). So, secondary protons, formed from the neutron decay, may exist at these distances, and they either interact with the gas there or escape from the AGN.

These different studies agree, at least, on the following: very high-energy particles originating in the central region are likely to be destroyed in the environment of the central region of an AGN, before they escape from their source. Thus, we take as the maximum energy of cosmic rays escaping from AGNs (from the central region not associated with jets, because higher-energy cosmic rays could be formed at the hot-spots in jets of some radio loud AGNs and then escape), the value

\[
E_{\text{max}} = 10^{19} \text{ eV} \quad .
\] (3.13)
The other parameters that are needed to calculate the cosmic ray propagation are those connected with AGN luminosity evolution. Recent works (Boyle et al., 1988; Boyle et al, 1990) show that the luminosity evolution of AGNs is best modeled by the following relation:

\[ L \propto (1 + z)^m \text{ with } m = 3.2 \quad . \tag{3.14} \]

This value for \( m \) is in good agreement with observations for redshifts, \( z \), lower than 2.5. For higher redshifts is very hard to determine the evolution parameter \( m \). For our calculations, we extrapolate the known result for low redshifts up to \( z=5 \). In fact, \( z_{\text{max}} = 5 \) is the maximum redshift we consider in most calculations. This value is about the smallest upper limit consistent with observations: the highest redshift associated with a quasar (PC 1247+340) is \( z=4.897 \).

### 3.5.3 Results

To obtain an upper limit for the flux emitted by each source, we need to integrate \( j(E) \) over the desired energy range, and then compare the result with the measured cosmic ray spectrum. In the calculation we use \( H_0 = 100 \text{ Km/s/Mpc} \) to find the Hubble radius \( R_0 \), and \( n_0 = 10^5/R_0^3 \) for the present number density of AGNs (Osterbrock, 1991). The results of our calculations are shown in Figures 3.2, 3.3 and 3.4. The different models are characterized by the different values for the spectral index of the cosmic ray flux and for the cosmic ray luminosity of each AGN. We vary the spectral index between \( \alpha = 1.7 \) to \( \alpha = 2.3 \) and the cosmic ray luminosity between \( 10^{43} \) to \( 10^{46} \) ergs/s. Figure 3.2 shows the results for \( \alpha = 2 \), using the two extreme luminosities. We are interested only in summed AGN cosmic rays fluxes that are significantly below the observed flux, since the latter is mainly Galactic (see Chapter 2); we consider the AGN fluxes that are above the observed flux to be inadmissible. This is exactly what happens in the case with \( L_{\text{CR}} = 10^{46} \) ergs/s, in Figure 3.2. So, from this model (\( \alpha = 2 \)), we find that the cosmic ray luminosity in the AGN must be lower than \( 10^{45} \).
ergs/s, in order to not contradict the observations. When we decrease the spectral index to \( \alpha = 1.7 \) (Figure 3.3), the problem is aggravated: Now, the cosmic ray luminosity in the AGN must be lower than \( 10^{44} \) ergs/s. In contrast, when we increase the spectral index to \( \alpha = 2.3 \) (Figure 3.4), we can allow the cosmic ray luminosity to be as large as its maximum likely value, \( L = 10^{46} \) ergs/s. However, as it was discussed above, the acceleration mechanisms in quasars tend to favor a spectrum flatter than \( \alpha = 2.3 \). Thus, the first two figures correspond to more suitable models.

The other parameters are fixed in this calculation, and their values have been justified previously. However, if we change them just to estimate the sensitivity of the results, we find the following behavior: (i) a variation of about 0.5 in the evolution parameter \( m \) (taken to be 3.2) does not change significantly the result of cosmic ray flux coming from AGNs. (ii) A variation in the maximum redshift, from \( z_{\text{max}} = 5 \) (the value used in our models) to \( z_{\text{max}} = 10 \), changes dramatically the quasar cosmic ray flux. The received flux coming from AGNs increases a large amount, as a direct consequence of counting more quasars, with higher luminosity. (iii) An increase in the maximum cutoff energy, by an order of magnitude, shifts the steepest part of the received AGN cosmic ray flux towards higher energies. Again, this increases significantly the total cosmic ray flux coming from AGNs. But, in this case, we would need to take into account the interactions of the highest-energy cosmic rays with the cosmic background radiation.

The work presented in this chapter provides some limits on the cosmic ray luminosity and spectrum in AGNs. Some values of key parameter are ruled out by the observations, but others are still consistent with them. In the following chapters, we use the most suitable models obtained above to develop the main part our work, that is, to study the effect of cosmic rays on the local AGN gas. We are able to obtain further, stronger constraints on the cosmic ray fluxes, by comparing the results of our calculations with what we know about the AGN gas (from analysis of the observed spectra).
Figure 3.2 Calculated cosmic ray flux from AGNs received at Earth (discontinuous lines) compared to the total observed flux (solid lines). The result is shown for an AGN cosmic ray luminosity of $10^{43}$ and of $10^{46}$ erg/s. In this model, each AGN emits a flux with differential spectral index $\alpha = 2$. 
Figure 3.3  The same as Figure 3.2 for a model with $\alpha = 1.7$. 
Figure 3.4  The same as Figure 3.2 for a model with $\alpha = 2.3$. 

$\alpha = 2.3$

- Observed $L_{\text{tor}} = 10^{46} \text{ erg/s}$
- $L_{\text{tor}} = 10^{43} \text{ erg/s}$

$log (\text{Energy})$
Chapter 4

SPALLATION IN AGNs

4.1 Formation of Light Elements

Except for $^7$Li, isotopes of the light elements Li, Be and B are produced in very small amounts in the Big Bang, and in stellar nucleosynthesis. Their formation is not favored in high temperature or high density environments due to the fragility of their nuclei. For instance, all of the $^7$Be and $^7$Li formed in the interior of the stars through the p-p chain interact with protons to produce unstable isotopes that eventually decay to He. Thus, there are no light elements left from this chain of reactions. The CNO cycle does not form any Li, Be or B either. The rest of the elements formed in massive stars (by burning consecutive layers in their interior or by exploding as a supernova) are heavier still (Clayton, 1983). In the Big Bang the reactions are different from those in stellar nucleosynthesis, due to the presence of neutrons and to both the higher temperature and the lower density. In this case, $^7$Li can be formed through the reaction: $^4$He + $^3$H → $^7$Li + γ, and through the decay of $^7$Be. However, the other light elements either decay or interact with protons and α particles to form heavier elements (Wagoner, 1973; Borner, 1992). Lists of the reactions involving formation and destruction of Li, Be and B in stellar and primordial nucleosynthesis are given, respectively, in Table 4.1 (Clayton, 1983) and Table 4.2 (Wagoner, 1973; Yang et al, 1984).

An environment with low temperature and density, yet some high-energy particles, is needed to produce even modest amounts of light elements. Their formation can then be given through the following processes:
\begin{center}
\begin{tabular}{|l|}
\hline
$^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$ \\
$^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu$ \\
$^7\text{Li} + H \rightarrow ^4\text{He} + ^4\text{He}$ \\
$^7\text{Be} + H \rightarrow ^8\text{B} + \gamma$ \\
$^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu \text{ (}$\beta$\text{ decay)}$ \\
$^8\text{Be} \rightarrow 2^4\text{He} \text{ (}$\alpha$\text{ decay)}$
\hline
\end{tabular}
\end{center}

\textbf{Table 4.1} Reactions involving stellar (proton-proton) nucleosynthesis of Li, Be and B.
\begin{align*}
^{3}\text{He} + \alpha &\rightarrow ^{7}\text{Be} + \gamma \\
^{4}\text{He} + t &\rightarrow ^{7}\text{Li} + \gamma \\
^{4}\text{He} + \alpha + n &\rightarrow ^{9}\text{Be} + \gamma \\
^{6}\text{Li} + p &\rightarrow ^{7}\text{Be} + \gamma \\
^{6}\text{Li} + n &\rightarrow ^{3}\text{H} + \alpha \\
^{6}\text{Li} + p &\rightarrow ^{3}\text{He} + \alpha \\
^{6}\text{Li} + \alpha &\rightarrow ^{10}\text{B} + \gamma \\
^{7}\text{Li} + p &\rightarrow ^{4}\text{He} + \alpha \\
^{7}\text{Li} + \alpha &\rightarrow ^{11}\text{B} + \gamma \\
^{7}\text{Be} + n &\rightarrow ^{7}\text{Li} + p \\
^{7}\text{Be} + p &\rightarrow ^{8}\text{B} + \gamma \\
^{7}\text{Be} + d &\rightarrow ^{4}\text{He} + p + \alpha \\
^{7}\text{Be} + \alpha &\rightarrow ^{11}\text{C} + \gamma \\
^{9}\text{Be} + p &\rightarrow ^{6}\text{Li} + \alpha \\
^{9}\text{Be} + p &\rightarrow ^{24}\text{He} + d \\
^{9}\text{Be} + p &\rightarrow ^{10}\text{B} + \gamma \\
^{10}\text{B} + p &\rightarrow ^{11}\text{C} + \gamma \\
^{10}\text{B} + p &\rightarrow ^{7}\text{Be} + \alpha \\
^{11}\text{B} + p &\rightarrow ^{12}\text{C} + \gamma \\
^{11}\text{B} + p &\rightarrow ^{24}\text{He} + \alpha 
\end{align*}

Table 4.2 Reactions involving primordial nucleosynthesis of Li, Be and B.
• Spallation: Interactions of very energetic protons and alpha particles with $^4$He, C, N and O nuclei, producing Li, Be and B.

• Photoerosion: Interactions of high-energy photons with the same nuclei, producing again Li, Be and B.

• Neutrino induced processes: Interactions of high-energy $\mu$ and $\tau$ neutrinos with heavy elements, fragmenting the nuclei and producing rare isotopes, from $^7$Li and $^{11}$B up to $^{180}$Ta.

Spallation has been the most studied of these processes; galactic cosmic rays interacting with interstellar matter provide the suitable conditions for this process to occur. Recent studies in this area (e.g., Walker, Mathews and Viola, 1985) have led to significant conclusions: Spallation reactions involving galactic cosmic rays can almost completely account for the observed, relative, elemental abundances of Be and B. However, to produce the observed $^{11}$Be/$^{10}$Be ratio, it is necessary to add a hypothetical low-energy cosmic ray component to the observed cosmic ray spectrum. But, in doing so, Li tends to be overproduced (Prantzos et al, 1993).

Photoerosion has been considered in an active galactic nuclei (AGN) scenario, where a high flux of $\gamma$ rays is present to interact with the local gas. The most recent studies (Boyd and Fendl, 1991) have included some new reactions, which may directly form significant amounts of $^7$Li. These calculations show that the abundances of $^7$Li, as well as Be and B in the Galactic disk, are high in a region close to the central engine of the AGN; they decrease beyond a certain radius which is typically of the order of 1 pc, but can be larger for a stronger incident $\gamma$ ray flux. The light elements so formed may diffuse into the extended gas of the active nucleus' host galaxy.

Finally, neutrino processes have been considered in supernova explosions, where large fluxes of neutrinos are released, and their probability of interaction with the gas is much higher than in any other environment. These processes could provide the
observed $\frac{^{11}_{12}B}{^{10}_{12}B}$ ratio which, as mentioned above, cannot be attained through spallation (Woosley et al, 1990).

Each of these processes can be important in its own environment, and a combination of them is probably needed to explain the abundances of light elements. In this chapter, we investigate an important aspect of one of them: spallation processes in AGNs. Spallation is the process most likely to occur in the extended emission line region of the AGN. Consequently, it affects the bulk of the of AGN gas and it may produce large amounts of light elements. Furthermore, the results of the light element production through this process can be used to put limits on the cosmic ray flux that must exist in AGNs. The one study previously done in this area (Baldwin et al, 1977) needs to be revised due to its incomplete spallation reaction network and crude AGN model.

4.2 Diffusion Models

Any simple diffusion model (one without energy losses, decay of particles or nuclear reactions) can be derived from the following equation:

$$\frac{\partial N}{\partial t} = \nabla (D \nabla N) + Q,$$  \hspace{1cm} (4.1)

where $N$ is the particle density, $D$ is the diffusion coefficient and $Q$ is the source of particles. Special scenarios may allow one to make some approximations in the above diffusion equation. Theses are discussed next, by an examination of two limiting diffusion models.

4.2.1 Distributed Sources in the Milky Way

A residence time $\tau$ for the cosmic rays in the Galaxy can be obtained from the analysis of observed spallation products (specifically, from $^{10}$Be, which has a decay time of $3.6 \times 10^6$ years). This time is found to be $\tau \simeq 2 \times 10^7$ years (Gaisser, 1990). If cosmic rays were to propagate straight through the interstellar medium at almost the
speed of light, then the time to cross the Galaxy and escape from it is only about $10^4$ years. Evidently, cosmic rays are scattered many times, probably by irregularities in the magnetic field, before they escape from the Galaxy. Therefore, to study cosmic ray propagation in our Galaxy we need a diffusion model, whose parameters must be adjusted to yield consistency with the observations.

The diffusion model most commonly used is the "leaky box" model. This model describes a galaxy in which the cosmic ray sources are distributed uniformly. Cosmic rays move in the considered region (or box) until they reach the edge, where they have a certain probability of escaping. The model yields an exponential distribution of path lengths for the accelerated particles. There exists a characteristic amount of material traversed $\Lambda$, which is related to the residence time $\tau$ by

$$\Lambda = \rho v \tau$$ \hspace{1cm} (4.2)

where $\rho$ is the mean gas density and $v \approx c$ the particle velocity. The value of $\Lambda$ for our Galaxy is approximately 6 g cm$^{-2}$ (Longair, 1981; Meneguzzi, Audouze and Reeves, 1971).

In the "leaky box" model, the residence time plays an important role in the diffusion-loss equation for cosmic rays; the diffusion term is approximated by the cosmic ray number density divided by $\tau$. So the diffusion equation (without any source term) becomes simply

$$\frac{\partial N}{\partial t} = -\frac{N}{\tau}$$ \hspace{1cm} (4.3)

Here, there is no density dependence on position, i.e., there is no gradient of cosmic rays from one region to another.

The "leaky box" model is in fair agreement with the observations. More sophisticated diffusion models do not improve the results of the diffusion-loss equation significantly, so they are not used to treat the secondary products (i.e. the "leaky box" model cannot explain some aspects of the observational data, but the other models cannot explain them either; Gaisser, 1990)
We also can relate the "leaky box" model to a pure diffusion model. In doing so, we can obtain a diffusion coefficient and, consequently, estimate a size for the irregularities that are responsible for the scattering processes. The main difference between a pure diffusion model and a "leaky box" model is that in the former case the cosmic rays originate in a central source, so they are not homogeneously distributed as they are in the latter case. This model results in a gaussian distribution of path lengths and cosmic rays. If we want to relate one model to the other, we need to calculate a mean density of cosmic rays in some region of interest, and assume that the cosmic rays are uniformly distributed therein.

In a pure diffusion model, we can find the diffusion coefficient $D$ by using the relation

$$ D = \frac{L^2}{\tau}, \quad (4.4) $$

where $L$ is the dimension of the region considered. For our Galaxy, we take $L$ to be about the height of the disk, 700 pc, and $\tau = 2 \times 10^7$ years (Longair, 1981; Gaisser, 1990). Then, $D$ is $3 \times 10^{28}$ cm$^2$/s. We can also find the diffusion mean free path $\lambda$ from another diffusion relation,

$$ D = \frac{\lambda u}{3} \approx \frac{\lambda c}{3}, \quad (4.5) $$

and $\lambda$ turns out to be about 1 pc. This result is a reasonable match to the size of irregularities in the Galactic magnetic field or in the density of the interstellar medium (Longair, 1981; Gaisser, 1990). Finally, we can also define an average velocity for diffusive escape from the Galaxy,

$$ v_{\text{esc}} \sim \frac{D}{L} \sim 10^{-3}c \quad (4.6) $$

Again, this shows that the energetic particles do not move straight through the interstellar medium. Altogether, these diffusion parameters describe quite well the propagation of cosmic rays in the Galaxy.
4.2.2 Point Source in an AGN

So far, we have reviewed diffusion models as they apply to our Galaxy (now). But, we are mostly interested in the inner, so-called narrow line regions (NLR) of active galaxies, which typically extend up to 100 pc from the central source. In this case, the initial source of cosmic rays is quite different from that of our Galaxy: cosmic rays are constantly accelerated outwards from the AGN central engine. Their propagation through the NLR is illustrated schematically in Figure 4.1. This suggests a pure diffusion model, in which the source term in Eq. 4.1 can be written as

\[ S(r, t) = S_0 \delta(r), \quad t_0 + T_{\text{AGN}} \geq t \geq t_0 \]

\[ = 0, \quad \text{otherwise} , \]

(4.7)

where \( S_0 \) will be fixed by the cosmic ray luminosity. The interval \((t_0, t_0 + T_{\text{AGN}})\) represents the period of high galaxy “activity.” In this case, the Green's function for the diffusion equation satisfies

\[ \left( \frac{d}{dt} - D \nabla^2 \right) G = \delta(r) \delta(t) , \]

(4.8)

and is, therefore,

\[ G(r, t) = \left( \frac{1}{4\pi Dt} \right)^{3/2} \exp^{-r^2/4Dt} . \]

(4.9)

To obtain the corresponding density distribution of cosmic rays now we need to integrate over position and time:

\[ N(r, t - t_0 \leq T_{\text{AGN}}) = \int dr' \int dt' G(r - r', t - t') S(r', t') \]

(4.10)

\[ = \frac{S_0}{(4\pi D)^{3/2}} \int_{t_0}^{t_0 + T_{\text{AGN}}} dt' \left( \frac{1}{t' - t} \right)^{3/2} \exp^{-r^2/4D(t - t')} \]

(4.11)

Evaluation of this integral gives

\[ N(r, t - t_0 \leq T_{\text{AGN}}) = \frac{S_0}{4\pi D} \text{erfc} \sqrt{\frac{r^2}{4\pi D(t - t_0)}} . \]

(4.12)

This solution provides the following behavior for the particle distribution: In a certain position, far away from the source, the density is first negligible and, then, it increases
Figure 4.1 Cosmic rays originating in the central region of an AGN diffusing out through its narrow line region.
suddenly with time until it gets to essentially a constant value. This long-time value is:

$$\lim_{(t-t_0) >> 2^\pi D/4\pi D} N(r, t) \sim \frac{S_0}{4\pi D}$$

(4.13)

At any given time, the particle density decreases with increasing distance from the source. As it can be seen in the above limiting result of the asymptotic value, after a sufficiently long time the density is just inversely proportional to the distance. This limit is only valid for $t-t_0 \leq T_{AGN}$, since during this time there is a constant source of particles. If the source becomes zero for $t-t_0 > T_{AGN}$, then the particle density at very large times will asymptotically reach zero also. The way the source term decays after $T_{AGN}$ is only relevant at times near $T_{AGN}$, but it is not important at very large times. However, if we consider the evolution of a real galaxy, it is likely that the source term reaches a lower constant value rather than zero, after the galaxy has passed an active phase. In the non-active phase, there will be a uniform distribution of sources instead of a point source, as in the leaky-box scenario.

In order to investigate our specific case, we need to use the parameters corresponding to the NLR of the AGNs. Unfortunately, we do not know the value of the diffusion coefficient in an AGN environment, but we first assume that it is comparable to the one for our Galaxy. (We will see later that this is probably an upper limit to the actual diffusion coefficient in the AGN, and we will estimate a more suitable value, according to the NLR properties. For now, we use the Galactic coefficient because its value is well known. Then, the different results can be compared to find their sensitivity on the diffusion coefficient.) So, if we put $D = 3 \times 10^{28} \text{ cm}^2/\text{s}$, $R=100 \text{ pc}$ for the characteristic dimension of the NLR, and $T_{AGN} = 10^8 \text{ yr}$ for the characteristic time that the AGN has been active (Rees, 1984), we find that the particle density has already reached a constant value. This is illustrated in Figure 4.2, which displays a numerical evaluation of Equation 12. In fact, since the characteristic escape time for the NLR is $\tau \sim R^2/D \sim 10^5 \text{ years}$, for any time much larger than $\tau$ the particles flow through the NLR at a constant rate.
Figure 4.2  Density of cosmic rays in the narrow line region, as a function of position from AGN center, plotted for different diffusing times and using the Galactic diffusion coefficient. We set $t_0 = 0$. 
If we do not consider the central region ($r \leq 10$ pc), where the particles are accelerated and the cosmic ray density is very large, we see from Figure 4.2 that the surrounding NLR has a density of cosmic rays that does not vary much with position. We determine a mean cosmic ray density for the NLR and consider that it is basically a spherical "box" from which the cosmic rays escape in a characteristic time $\tau = 10^5$ years. If the accelerated particles could move freely through the NLR, they could escape in about $10^3$ years. This implies that the average cosmic ray diffusion speed is about $v_{esc} \approx 0.01c$.

However, the real diffusion coefficient in an AGN is likely to be smaller than that in our Galaxy, since the AGN magnetic field is thought to be larger, $B_{NLR} \approx 10^{-4} G \approx 10^2 B_{Gal}$ (Osterbrock, 1991; Emmering, Blandford and Shlosman, 1992), and the size of inhomogeneities in the AGN material is smaller. We use the latter to estimate the value of the diffusion coefficient. The gas in the emission line region of the AGN is distributed in dense clouds with dimensions of the order of $\sim 10^{14}$ cm (Osterbrock, 1984). Since the filling factor of these clouds is usually $f = 10^{-2} - 10^{-3}$ (Osterbrock, 1984), then the typical distance between them is about $10^{-2}$ pc. This distance can be interpreted as a diffusion mean free path, $\lambda$. As it was said above, the corresponding value for the interstellar medium of our Galaxy is $\sim 1$ pc. By using the definition of diffusion coefficient (Eq. 4.5), for $v \sim c$, we find that

$$D_{NLR} = \frac{1}{3} \lambda v \approx 10^{-2} D_{Gal} \approx 3 \times 10^{26} \text{cm}^2\text{s}^{-1}.$$  \hspace{1cm} (4.14)

We obtain a new set of results for the cosmic ray density as a function of time and position using the diffusion coefficient estimated for the NLR. Figures 4.3 and 4.4 compare some results obtained using $D_{Gal}$ with those using $D_{NLR}$. For $D_{NLR}$, we find that the characteristic diffusion time is increased to $\tau \sim 10^7$ years. This yields an effective velocity of $10^{-4}$ c. Even though it takes much longer for the particles to pass through the NLR, the diffusion time is still one order of magnitude smaller...
Figure 4.3  Density of cosmic rays as a function of distance from the central region, for two diffusion coefficients (Galactic and NLR), and after $10^8$ years.
Figure 4.4 Density of cosmic rays as a function of time, for 2 diffusion coefficients (Galactic and NLR), and at two distances from the center (10 pc and 100 pc).
than the AGN lifetime. Thus, at about $10^8$ years and at distances $\leq 100$ pc from the center, the flux again will have reached a nearly constant value.

In summary, the distribution of cosmic rays in the NLR of AGNs can be described by a pure diffusion model. However, the resulting distribution in the region and time of interest is sufficiently smooth to allow a reasonable estimation of the mean value for the cosmic ray density, and then to compare it with the distribution in a "leaky box" model. The "box" (or shell, in this case) that represents the NLR has very different properties than the Galactic "leaky box": (i) the mean cosmic ray density is much larger, (ii) the gas density is also larger, (iii) its size is much smaller, and (iv) the magnetic field strength is likely to be two orders of magnitude greater. A complete list of the differences between the two cases is presented in Table 4.3. These properties provide unusual values for the parameters, such as $\Lambda$, used in the (general) diffusion-loss equation for cosmic rays or for spallation products. An extensive description of this equation, as well as the way it is solved, is presented in the next section.

4.3 Calculations

4.3.1 Diffusion-Loss Equation for Cosmic Rays

In the previous section, we calculated a mean density of cosmic rays in the NLR ($R \sim 100$ pc) using a pure diffusion model. Here, we use that density and the injected power-law flux of cosmic rays to calculate their equilibrium spectrum after they have suffered energy losses in this region. The spectrum for protons and alpha particles is obtained by solving the diffusion-loss equation (e.g., Prantzos, Casse and Vangioni-Flam, 1993)

$$\frac{\partial N(E)}{\partial t} = Q(E) - \frac{N(E)}{\tau} + \frac{\partial}{\partial E} \left( b(E)N(E) \right),$$  \hspace{1cm} (4.15)

where $Q(E)$ is the source of primary cosmic rays and $b(E)$ is the energy loss rate (eV/s). Nuclear reactions are not included because they do not modify significantly the primary cosmic ray equilibrium spectrum (Prantzos, Casse and Vangioni-Flam,
### Milky Way \hspace{1cm} Active Galactic Nuclei

<table>
<thead>
<tr>
<th>Gas Characteristics</th>
<th>Milky Way</th>
<th>Active Galactic Nuclei</th>
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<td><strong>Interstellar Medium (ISM)</strong></td>
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<td>(R = 100) pc</td>
</tr>
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<td>(10^2) cm(^{-3}) ((u \cdot f))</td>
</tr>
<tr>
<td>(CNO) Abundance</td>
<td>Population I (Solar)</td>
<td>Population I or Population II</td>
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<tr>
<td>Lifetime</td>
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<td>(10^8) yr</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>(B_{\text{Gal}} = \text{few} \mu\text{G})</td>
<td>(B_{\text{NLR}} = 10^2 \ B_{\text{Gal}})</td>
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<td>Diffusion Coefficient</td>
<td>(D_{\text{Gal}} = 3 \times 10^{28}) cm(^2)s(^{-1})</td>
<td>(D_{\text{Gal}}) \hspace{1cm} or \hspace{1cm} (D_{\text{NLR}} = 10^{-2} D_{\text{Gal}})</td>
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<tr>
<td>Diffusion Time</td>
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<td>(\tau = 10^5) yr \hspace{1cm} (\tau = 10^7) yr</td>
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<td>Escape Parameter</td>
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<td>(\Lambda = 15) g cm(^{-2}) \hspace{1cm} (\Lambda = 1500) g cm(^{-2})</td>
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<td>CR Luminosity</td>
<td>(10^{41}) erg s(^{-1})</td>
<td>(10^{44} - 10^{46}) erg s(^{-1})</td>
</tr>
<tr>
<td>Flux: (\Phi = K \left( \frac{E}{E_0} \right)^{-\alpha})</td>
<td>(\alpha \geq 2.5) \hspace{1cm} (E_0 = 10^9) eV</td>
<td>(1.7 \leq \alpha \leq 2.3) \hspace{1cm} (E_0 = 10^7) eV</td>
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<tr>
<td>(CNO)(_{\text{CR}})</td>
<td>observed abundances</td>
<td>assume Galactic values</td>
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**Table 4.3** Comparison of diffusion-spallation models
1993). We consider steady-state ($\partial N/\partial t = 0$) conditions, since the cosmic ray density at 100 pc from the center does not change practically with time, for times larger than the diffusion time (see Figure 4.4). We are interested in what has happened in an AGN lifetime, hence $t - t_0 \geq T_{AGN} = 10^8$ years, which is always larger than the diffusion time $\tau$ for all reasonable values of the diffusion coefficient.

The diffusion-loss equation can be re-written in terms of the local flux $F(E)$. We multiply Eq. 4.15 by $c$ and divide by the mean gas density to get:

$$\frac{\partial F(E)}{\partial X} = q(E) - \frac{F(E)}{\Lambda} - \frac{\partial(\omega F(E))}{\partial E} = 0 \quad . \quad (4.16)$$

Now $X$ is the amount of matter traversed (g cm$^{-2}$) and $\omega = b/\rho v$ is the rate of energy loss in eV cm$^2$ g$^{-1}$. The value for the characteristic amount of material traversed, $\Lambda$, depends on the density of the gas and the diffusion time $\tau$ (Eq. 4.2). At the same time, $\tau$ depends on the diffusion coefficient. If we adopt the Galactic diffusion coefficient, then $\Lambda \approx 15$ g cm$^{-2}$. But, if we use the value of the diffusion coefficient estimated for the NLR, $D_{NLR} \approx 10^{-2}D_{Gal}$, then $\Lambda \approx 1500$ g cm$^{-2}$. The source parameter $q(E)$ also is different for the two different diffusion coefficients. Its value is calculated by multiplying the density of cosmic rays at 100 pc, which depends on $D$, by $c$ and dividing by the mean density of the gas. This mean gas density is found by multiplying the filling factor of the NLR clouds, $f = 10^{-2}$, with the gas density of the clouds, $n = 10^4$ cm$^{-3}$. We neglect here the contribution of the intercloud gas to the mean density because it is very tenuous ($n_{ic} \approx 1$ cm$^{-3}$) compared with the cloud gas.

Most of the energy losses for the primary cosmic rays are due to ionization losses, as they encounter the gas in the NLR. In order to estimate the rate of ionization losses, we use the Bethe-Bloch formula, which describes the scattering of a moving particle of charge Ze by an electron at rest, and it has the following form (Ginzburg, 1989),

$$-\frac{dE}{dz} = \frac{1}{v} \frac{dE}{dt} = \frac{2\pi e^4 Z^2 n_e}{mv^2} \ln \frac{2mv^2 W_{max}}{I^2(1 - \beta^2)} - 2\beta^2 + \delta \quad , \quad (4.17)$$
where $n_e$ is the electron density, $m$ is the electron mass, $\beta = v/c$, $v$ is the velocity of the moving charge, $I$ is the mean ionization energy for the atoms in the gas, $W_{\text{max}}$ is the highest energy transferred from the particles to the atomic electrons, and $\delta$ is a correction term accounting for the "density effect". For an ionized gas and all but ultrarelativistic particles, the general expression takes the form

$$\frac{dE}{dt} = 7.62 \times 10^{-9} Z^2 N \left( \frac{2Mc^2}{E_k} \right)^{1/2} \left( \ln \frac{E_k}{Mc^2} - \frac{1}{2} \ln N + 38.7 \right) \text{ eV s}^{-1}, \quad (4.18)$$

where $E_k$ is the kinetic energy and $M$ is the mass of the moving particle. The contribution of very high energy particles which decay to lower energies (i.e., to the $10^7$ eV to $10^{12}$ eV energy range where spallations are more efficient) can be neglected, because the number of particles decreases rapidly with increasing energy due to the steep power-laws.

If we substitute the values for our case, we find that $\omega \approx 10^7$ eV cm$^2$ g$^{-1}$ for protons (in order to get these units we need to multiply Eq. 4.17 by $6 \times 10^{23} n_e^{-1}$).

The solution to the steady-state diffusion-loss equation (Eq. 4.16) is then

$$F(E) = \frac{1}{w} \int_E^\infty q(E') \exp \left( -\frac{R(E') - R(E)}{x} \right) dE', \quad (4.19)$$

where $R(E) = \int_0^E \frac{dE''}{w(E'')}$ is the ionization range. We calculate numerically the proton cosmic ray spectrum (which is 90% of the total cosmic ray spectrum) in the NLR, using the value of $R$ for protons and the values of $\Lambda$ for the two different diffusion coefficients. The rest of cosmic rays are mostly alpha particles; the same calculation can be done to obtain their equilibrium spectrum using the corresponding ionization range. The resulting equilibrium spectrum is shown in Figure 4.5 for the two diffusion coefficients that were used to obtain $\Lambda$ and $q(E)$ ($D_{Gal}$ and $D_{NLR} = 10^{-2} D_{Gal}$). We only show the result corresponding to Model 2 of Chapter 3 (i.e., for $L_{CR} = 10^{45}$ erg/s and $\alpha = 2$).

For the other two models (also defined in Chapter 3), a change in the diffusion coefficient modifies the injected power-law in the same fashion as for Model 2. This
Figure 4.5  Cosmic ray flux with ionization losses, at 100 pc from the center and after $10^8$ years.
is how the spectrum is modified: The amount of cosmic rays that can interact with
the gas is larger when the diffusion coefficient is smaller because the same number of
particles are trapped in a smaller region. In addition, for a smaller diffusion coefficient
the equilibrium spectrum is more modified with respect to the injected spectrum at
low energies (i.e., the spectrum is flatter at low energies). This is because the particles
have to go through more material before they escape from the NLR and, consequently,
yield more ionization losses. So, only particles with higher energy can escape
the region without first losing their energy.

4.3.2 Spallation Reactions

The primary cosmic rays, with spectrum \( F(E) \), interact with the nuclei in the NLR
and produce Li, Be and B through spallation reactions. The most important set of
reactions are those involving H and He cosmic rays and He, C, N and O in the gas.
Their complementary reactions (C, N, and O cosmic rays interacting with the H and
He in the gas) contribute only about 20% to the total result, even for a gas with solar
abundances (Meneguzzi and Reeves, 1975).

We first consider H and He cosmic rays in the energy range of \( 10^7 - 10^{12} \) eV,
because lower-energy cosmic rays are below the spallation reaction thresholds and
higher-energy cosmic rays do not contribute significantly to the production of light
elements. When H and He cosmic rays interact with massive particles which have
thermal velocities, most of the light elements that are formed have low velocities. This
means that these products are likely to be thermalized very rapidly and, consequently,
that they do not escape from the region where they are formed. Thus, the rate at
which light elements produced through these reactions are added to the NLR can be
expressed in the following way (Meneguzzi, Audouze and Reeves, 1971):

\[
\frac{\partial n_i}{\partial t} = \sum_k \int_{E_{\text{thres}}}^{10^{12} \text{eV}} [\sigma_{pkl} F_p(E) + \sigma_{akl} F_a(E)] n_k dE ,
\]  

(4.20)
where $\sigma_{pkl}$ and $\sigma_{\alpha kl}$ are the spallation cross sections for proton and $\alpha$ particles respectively, interacting with an isotope $n_k$ from the gas to produce a light isotope $n_l$. These cross sections are derived from Read and Viola, 1984, who present all the existing data for spallation cross sections in different ranges of energy. They fit the experimental values to a smooth curve, referred to as the excitation function (in their fit they assume that the cross section is 0.01 mb at threshold, where usually there is a lack of data). They list the excitation functions for a proton and an $\alpha$ particle reacting with C, N and O and forming a light element of $A \geq 6$, but they do not distinguish between Li, Be or B. We use these excitation functions plus their collection of experimental data, which provide information about what specific nucleus is formed, to infer an excitation function for each Li, Be and B isotope. These excitation functions are discussed and plotted in Appendix C. The energy threshold for these reactions is usually about 20 MeV, and the cross section peaks at about 50 MeV before dropping to a constant value at $\sim 100$ MeV. In addition, we use the excitation function for the nuclear reaction $^4\text{He} + ^4\text{He} \rightarrow ^6\text{Li}$, $^7\text{Li}$ and $^7\text{Be}$, which has almost the same behavior as those for the spallation reactions, but the peak is much sharper and the constant value at higher energies is larger. The shape of these cross sections curves will be important in order to understand our computed results (Prantzos et al, 1993).

The spallation products predicted by Eq. 4.20 are sensitive to the abundances of C, N and O in the NLR gas. Observations suggest that element abundances are nearly solar, perhaps with enrichment of heavy nuclei in the broad line region gas, (since that gas is closer to the central engine). Recent observations of iron at high redshift quasars favor early enrichment in the inner region (Elston, Thompson and Hill, 1994). But, there is no evidence that the composition of the NLR gas is enriched in metals to values much larger than solar (Trimble, 1991; Kwan, 1990). Thus, we use Population I abundances for the C, N and O in the gas. For comparison, we also have carried out a set of calculations using Population II abundance in the NLR gas.
We evaluate the integral of Eq. 4.20 numerically for the three flux models, also varying the diffusion coefficient \(D_{Gal}\) and \(D_{NLR}\) and the metallicity of the gas (Population I and Population II) in each model. Since the right-hand side of Eq. 4.20 does not depend on time, we obtain the abundance of light elements in the NLR by simply multiplying that side of the equation by the time during which cosmic rays are accelerated in the central region. This time corresponds to the lifetime of the AGN, which is about \(T_{AGN} \sim 10^8\) years. During all this time there are cosmic rays interacting with the surrounding gas, and, consequently, light elements being produced.

However, these are not the final results for the spallation products. We still need to include the complementary reactions. In this case, heavier (C, N and O) cosmic rays interact with low energy hydrogen and helium nuclei from the gas. These spallation products are likely to have enough energy to escape from the NLR, but not the host galaxy. In order to take this into account, we need to compare the ionization loss time for each product as a function of energy to the escaping (diffusion) time. We do not include in the final result the spallation products that have had time to escape before they lose their energy. This condition can be represented in terms of the ionization range and \(\Lambda\). Specifically, if

\[ \mathcal{R}(E) > \Lambda, \quad (4.21) \]

or, substituting for the values of \(\mathcal{R}(E)\) and \(\Gamma\), if

\[ 10^{-7} E(eV) > \rho c \tau = \begin{cases} 15, & \text{for } D_{Gal} \\ 1500, & \text{for } D_{NLR} \end{cases}, \quad (4.22) \]

then the products are assumed to escape from the NLR.

Observations show that the Galactic cosmic ray abundances for these elements are approximately solar (see Chapter 2). This is consistent with the theory that cosmic rays are mainly particles from the interstellar medium which have been accelerated in the shocks. An analogous argument can be applied to an AGN environment: it
is likely that the source of cosmic ray particles is the gas near the central engine, mainly the broad line region gas, where enrichment is supposed to occur very rapidly. Therefore, we take the relative C, N and O abundances in the AGN cosmic rays to be the same as in the Galaxy. Alternatively, high energy particles accelerated in extensive jets could come from outer parts of the host galaxy. In that case, the cosmic ray metallicity may be lower than that of population I stars. But, this is unlikely to affect spallation rates because these cosmic rays interact minimally with the narrow line region gas.

After including the complementary reactions in the numerical calculation, we obtain the final abundances in the NLR for the following isotopes: $^6$Li, $^7$Li, $^9$Li, $^9$Be, $^{10}$B and $^{11}$B. We calculate also the production of $^7$Be and $^{10}$Be, but they are $\beta$ unstable and decay almost completely to $^7$Li and $^{10}$B, respectively, during the AGN lifetime. The decay time for $^{10}$Be at rest is $3.6 \times 10^6$ years, which must be multiplied by the Lorentz factor. $^7$Be decays almost spontaneously, with a characteristic decay time of 54.5 days, again multiplied by the Lorentz factor. However, $^7$Be needs to capture an electron in order to decay, and the difficulty of capturing an electron increases as the isotope energy increases. Nevertheless, the $^7$Be that stays in the NLR has lost most of its energy by scattering with the gas particles, and will not be present in the region of interest for very long.

Our final results are collected in Table 4.4. As expected, Model 1 gives the lowest abundances of light elements, $\mathcal{L} = \text{Li}, \text{Be}, \text{or } B$, since it corresponds to the lowest cosmic ray luminosity ($10^{44} \text{ ergs/s}$), and Model 3 ($L_{CR} = 10^{46} \text{ ergs/s}$) gives the largest light element abundances in the NLR. For each model, a decrease in the diffusion coefficient of two orders of magnitude causes light element abundances to increase by more than two orders of magnitude. This is due to the combination of two effects: the increase of cosmic ray density in the NLR caused by the higher trapping at low diffusion coefficients, and the fact that ionization losses modify the spectrum at higher energies. The $\text{B}/\text{Be}$ ratio is smaller for Model 1 than for Models 2 and 3, varying
from 13 to 20. This is due to the change in the spectral index from one model to another: Model 1 has the flattest spectrum ($\alpha = 1.7$), which favors those reactions whose cross sections have a constant value at high energies (almost as large as the peak at low energies). This behavior is more characteristic of cross sections involving the formation of Be than cross sections involving the formation of B; therefore, the Be abundance increases slightly as the spectral index decreases.

The isotope abundances change slightly when the metallicity of the gas is changed from Population I to Population II. The main difference between the two cases is in the Li/(Be+B) ratio, which increases from 5 to 10 when the metallicity is decreased. This is due to the fact that in low-metallicity environments the nuclear reaction $^4\text{He} + ^4\text{He} \rightarrow ^6\text{Li}$ or $^7\text{Li}$ or $^7\text{Be}$ is the most dominant one. Therefore, Li is produced in larger amounts compared with the other two light elements.

These spallation products presented in Table 4.4 might be an upper limit to the actual values, since the cosmic ray spectrum could be flatter at low energies, near the threshold for the spallation cross sections. Thus, the lack of information on the change of the spectral index $\alpha$ at about 1 GeV (proton rest mass) gives an uncertainty in the results. If we consider that $\alpha$ decreases by 0.5 from $E > 1 \text{ GeV}$ to $E \leq 1 \text{ GeV}$, the spallation products decrease by no more than a factor of 5. This factor is an upper limit on the uncertainty of the results, since it is obtained by assuming that all the production of light elements occurs at threshold ($E \sim 2 \times 10^7 \text{ eV}$). If we also consider the contribution at higher energies, where the difference in cosmic ray flux is less than at threshold, then the uncertainty in the results is always lower than a factor of 5.

In the following chapters, these results first will be compared with upper limits for boron abundances obtained from the analysis of observed AGN spectra. Then, they will be discussed in connection with Big Bang nucleosynthesis production of light elements, as well as standard Galactic models of chemical enrichment.
### Model 1

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<tr>
<th>n(Ł)/n(H)</th>
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<th></th>
<th>$D_{NLR}$</th>
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<td>Pop II</td>
<td>Pop I</td>
<td>Pop II</td>
<td>Pop I</td>
<td>Pop II</td>
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<td>$^6$Li</td>
<td>$1.68 \times 10^{-10}$</td>
<td>$1.51 \times 10^{-10}$</td>
<td>$2.83 \times 10^{-8}$</td>
<td>$2.51 \times 10^{-8}$</td>
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<td>$^7$Li</td>
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<td>$5.96 \times 10^{-10}$</td>
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<td>$9.95 \times 10^{-11}$</td>
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<tr>
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<td>$2.33 \times 10^{-11}$</td>
<td>$8.43 \times 10^{-9}$</td>
<td>$4.25 \times 10^{-9}$</td>
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<tr>
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### Model 2

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**Table 4.4** Spallation products in the narrow line region of an AGN.
### Model 3

| n(Л)/n(H) | $D_{Gal}$ | | $D_{NLR}$ | |
|-----------|-----------|----------------|-----------|
|           | Pop I     | Pop II         | Pop I     | Pop II   |
| $^6$Li    | 9.17 $\times 10^{-5}$ | 8.23 $\times 10^{-5}$ | 1.46 $\times 10^{-2}$ | 1.31 $\times 10^{-2}$ |
| $^7$Li    | 4.01 $\times 10^{-4}$ | 3.82 $\times 10^{-4}$ | 5.70 $\times 10^{-2}$ | 5.41 $\times 10^{-2}$ |
| $^9$Li    | 2.18 $\times 10^{-7}$ | 1.10 $\times 10^{-7}$ | 3.98 $\times 10^{-5}$ | 2.01 $\times 10^{-5}$ |
| $^9$Be    | 4.36 $\times 10^{-6}$ | 2.19 $\times 10^{-6}$ | 7.67 $\times 10^{-4}$ | 3.87 $\times 10^{-4}$ |
| $^{10}$B  | 3.15 $\times 10^{-5}$ | 1.59 $\times 10^{-5}$ | 4.63 $\times 10^{-3}$ | 2.34 $\times 10^{-3}$ |
| $^{11}$B  | 5.84 $\times 10^{-5}$ | 2.95 $\times 10^{-5}$ | 8.66 $\times 10^{-3}$ | 4.37 $\times 10^{-3}$ |

*Table 4.4 (Continued).*
Chapter 5

SPECTROSCOPIC LIMITS ON BORON IN AGNs

5.1 Importance of a Boron Spectroscopic Limit

In this work, we have investigated different ways of setting limits on the cosmic ray flux originating in the central region of an active galactic nucleus. In Chapter 3, we used the cosmic ray spectrum observed on Earth to find the maximum possible contribution of cosmic rays from AGNs to the total spectrum. Since this contribution has been shown to be practically negligible (Chapter 2, Section 2), the calculated amount of cosmic rays coming from all AGNs must be well below the observed cosmic ray flux. By computing the propagation of cosmic rays from AGNs to Earth, we found that cosmic ray fluxes at each AGN \((F = F_0 E^{-\alpha})\) had to be lower than those corresponding to a cosmic ray luminosity of \(10^{46} \text{ erg s}^{-1}\) for \(\alpha = 1.7\), a cosmic ray luminosity of \(10^{45} \text{ erg s}^{-1}\) for \(\alpha = 2\), and of \(10^{44} \text{ erg s}^{-1}\) for \(\alpha = 2.3\). These cosmic ray luminosities also agreed with efficiency arguments. We argued that the power-law was unlikely to be flatter than \(\alpha = 1.7\) or steeper than \(\alpha = 2.3\), due to reasons related to the likely acceleration mechanism (Chapter 3, Section 3).

These upper limits on the cosmic ray luminosity, and their corresponding power-laws, were used to carry out spallation calculations in AGNs. In this case, the production of light elements, which is exclusively due to cosmic rays originating in the central region, can help to determine in a much more accurate way the amount of cosmic rays in that region. In Chapter 4, this spallation calculation was performed, and the resulting light element abundances in the narrow line region of the AGN
were presented for different models. These abundances are needed to obtain the strength of important emission lines of these elements, which might be detected in AGN spectra. In this chapter we focus on a BIII line, because it satisfies several desired characteristics. First of all, B$^{2+}$ is likely to be abundant at NLR conditions. It also has a UV line, BIII 2066Å, relatively strong compared to those of other abundant Li, Be and B ions. This can be seen by comparing the BIII oscillator strength with the oscillator strengths corresponding to the UV transitions of the other light ions (Table 5.1; Weise, Smith and Glennon, 1966). We are mainly interested in the wavelength range from 1800Å to 2800Å, for which there exist spectral data for a large number of quasars. We found that BIII 2066Å has the largest oscillator strength in this wavelength range. The oscillator strength can provide information about the actual strength of the line. In fact, for a permitted line, the collision excitation cross section is proportional to the oscillator strength, if one only considers the electric dipole contribution (see Seaton, 1962). Therefore, in the case that radiative decays balance collisional excitations, the strength of the line is also roughly proportional to the oscillator strength.

The spallation problem in quasars was addressed previously in a paper by Baldwin et al. (1977). However, the problem was worked in a very simplified way due to the paucity of data at that time. First of all, they used a cosmic ray luminosity between $10^{45}$ and $10^{50}$ erg s$^{-1}$, with all particles at 100 MeV. Our study on acceleration of energetic particles and their propagation through intergalactic space allowed us to derive a more realistic AGN cosmic ray flux. In addition, contrary to our work, their spallation calculation was done without using a diffusion model determined by a diffusion coefficient (based on the magnetic field strength in the region of interest). They then considered only spallation reactions for boron and used incomplete cross section data. We improved this aspect with a revised set of spallation cross sections (Read and Viola, 1984); the spallation calculation was performed for Li, Be and B in order to later relate this work to chemical abundance evolution. The physical
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<th>$f_{ij}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BeII</td>
<td>3130.6</td>
<td>0.505</td>
</tr>
<tr>
<td></td>
<td>1776.2</td>
<td>0.0665</td>
</tr>
<tr>
<td></td>
<td>1512.4</td>
<td>0.652</td>
</tr>
<tr>
<td></td>
<td>3274.64</td>
<td>0.0691</td>
</tr>
<tr>
<td></td>
<td>3247.7</td>
<td>0.0216</td>
</tr>
<tr>
<td>BeIII</td>
<td>3721.8</td>
<td>0.213</td>
</tr>
<tr>
<td>BII</td>
<td>1362.46</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>1623.99</td>
<td>0.082</td>
</tr>
<tr>
<td></td>
<td>1842.8</td>
<td>0.12</td>
</tr>
<tr>
<td>BIII</td>
<td>2066.3</td>
<td>0.366</td>
</tr>
<tr>
<td>BIV</td>
<td>2823.4</td>
<td>0.163</td>
</tr>
</tbody>
</table>

Table 5.1 Oscillator strengths for UV transitions of Li, Be and B.
conditions used in our study also were more realistic ($< n > = 10^4 \text{ cm}^{-3}$ and $f = 10^{-2}$ for the narrow line region), due to the existence of recent AGN observations and of more elaborate AGN models.

The last piece of information necessary for comparison of model results with observations (in order to obtain a stronger cosmic ray flux limit from the spallation study) is the ionization structure of boron in the AGN gas, and the strength of its emission lines. In the previous work (Baldwin et al., 1977), this was estimated by crude ionization arguments, without solving boron ionization balance equations. In our work, the ionization structure is solved in considerable detail.

All these differences between the approach followed in Baldwin et al. (1977) and the present work are summarized in Table 5.2.

### 5.2 Boron Ionization Structure

In steady-state, the ionization structure of boron is determined by a set of equations that balance ionizations with recombinations for each ionization stage of boron. Ionizations can be of an L-shell electron (probability per unit time, $\xi^L_r$) or of a K-shell electron ($\xi^K_r$). When K-shell ionizations occur in the system, then Auger transitions may need to be considered. Such transitions arise because electrons that remain in the outer shell may not decay radiatively. Instead, an electron may decay to the ground state by giving enough energy to another bound electron for it to escape from the ion. At the end, no photon has been emitted and the ion has been doubly ionized. A K-shell ionization leads to another ionization most of the time (98% probability) for atoms with at least four electrons (Weisheit and Dalgarno, 1972). The ions recombine by radiative and dielectronic processes (total rate coefficient, $\alpha_s$). All these processes can be included in the statistical balance for $B^0$, $B^+$, $B^{2+}$, $B^{3+}$ and $B^{4+}$, respectively, in the following set of equations:

\[
B^0 : \quad n_0 (\xi^K_0 + \xi^L_0) = n_1 n_e \alpha_1 \quad (5.1)
\]
<table>
<thead>
<tr>
<th><strong>Baldwin et al.</strong></th>
<th><strong>Present Work</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic Ray Luminosity</td>
<td>$10^{45} - 10^{50}$ erg/s</td>
</tr>
<tr>
<td>Cosmic Ray Flux</td>
<td>$E_{CR} = 100$ MeV</td>
</tr>
<tr>
<td>Diffusion Model</td>
<td>No diffusion coefficient</td>
</tr>
<tr>
<td>Ionization Losses</td>
<td>Neglected</td>
</tr>
<tr>
<td>Spallation Reactions</td>
<td>Only consider reactions for boron</td>
</tr>
<tr>
<td>Spallation Cross Sections</td>
<td>Use crude estimations (just an average constant value)</td>
</tr>
<tr>
<td>Gas Density</td>
<td>$n = 10^6$ cm$^{-3}$</td>
</tr>
<tr>
<td>Gas Radius</td>
<td>$R = 30$ pc</td>
</tr>
<tr>
<td>Residence Time</td>
<td>$\tau = 10^5$ yr</td>
</tr>
<tr>
<td>Boron Ionization Structure</td>
<td>Ionization balance equations not solved</td>
</tr>
</tbody>
</table>

Table 5.2 Differences between previous and present work related to spectroscopic limits on boron in AGNs
\[ B^+ : \quad n_1(\xi_1^K + \xi_1^L) + n_1 n_e \alpha_1 = n_0 \xi_0^L + n_2 n_e \alpha_2 \quad (5.2) \]
\[ B^{2+} : \quad n_2(\xi_2^K + \xi_2^L) + n_2 n_e \alpha_2 = n_1 \xi_1^L + n_0 \xi_0^K + n_3 n_e \alpha_3 \quad (5.3) \]
\[ B^{3+} : \quad n_3 \xi_3^K + n_e n_3 \alpha_3 = n_2(\xi_2^K + \xi_2^L) + n_1 \xi_1^K + n_4 n_e \alpha_4 \quad (5.4) \]
\[ B^{4+} : \quad n_4 \xi_4^K + n_4 n_e \alpha_4 = n_3 \xi_3^K + n_5 n_e \alpha_5 \quad (5.5) \]

Here, \( n_i \) is the population of the ionization state \( i \) and \( n_e \) is the electron density. The effect of Auger transitions is evident in Eqs. 5.2 and 5.3. All these equations can be simplified by defining an effective ionization rate \( \xi_{i}^{eff} \) (Weisheit and Dalgarno, 1972), such that:

\[ n_i \xi_{i}^{eff} = n_{i+1} n_e \alpha_{i+1} \quad (5.6) \]

For our case, we find

\[ \xi_{0}^{eff} = \xi_{0}^K + \xi_{0}^L \quad (5.7) \]
\[ \xi_{1}^{eff} = \xi_{1}^K + \xi_{1}^L + n_e \alpha_1 (\frac{\xi_{0}^K}{\xi_{0}^K + \xi_{0}^L}) \quad (5.8) \]
\[ \xi_{2}^{eff} = \xi_{2}^K + \xi_{2}^L + n_e \alpha_2 (\frac{\xi_{1}^K}{\xi_{1}^{eff}}) \quad (5.9) \]
\[ \xi_{3}^{eff} = \xi_{3}^K \quad (5.10) \]
\[ \xi_{4}^{eff} = \xi_{4}^K \quad (5.11) \]

In order to solve the simplified set of equations, we also need the conservation relation:

\[ n_B = n_0 + n_1 + n_2 + n_3 + n_4 + n_5 \quad (5.12) \]

Boron is important for a variety of astrophysical reasons, but a careful ionization balance has never been computed. Hence, we found it necessary to collect and/or calculate numerous atomic rate coefficients. We first calculated the K-shell and L-shell ionization rates (\( \xi^K \) and \( \xi^L \)) by using their corresponding photoionization cross sections. These photoionization cross sections were obtained from Rielman and Manson (1979), where they are numerically computed as a function of photon energy. Plots of their tabulated data are shown in Figures 5.1a, b, c and d for \( \text{B}^0 \), \( \text{B}^+ \), \( \text{B}^{2+} \) and \( \text{B}^{3+} \), respectively.
Figure 5.1 Total photoionization cross section in Mb ($10^{-18}$ cm$^2$) for different ionization states of boron.
Figure 5.1 (Continued).
These photoionization cross sections were then fitted to different power-laws, distinguishing between K-shell and L-shell photoionization. The fits are listed in Table 5.3. For B\textsuperscript{4+}, the photoionization cross section $\sigma$ was derived from the formula for a hydrogenic ion of nuclear charge $Z = 5$ (Osterbrock, 1984),

$$\sigma = \frac{\sigma_H}{Z^2} \left( \frac{E_{\text{threshold}}}{E(eV)} \right)^3$$

$$= 9.9 \times 10^{-12} E(eV)^{-3} \text{ cm}^2$$

for $E_{\text{threshold}} = 340$ eV and $\sigma_H = 6.3 \times 10^{-18}$ cm\textsuperscript{2}.

We obtained the photoionization rate by multiplying the boron cross sections $\sigma(E)$, by the radiation field from the central source, and integrating over energy. We include here absorption due to hydrogen atoms and helium atoms and ions. This is done by introducing an optical depth $\tau(E)$ into the integral in the following way:

$$\xi^{\text{Rad}} = \int_{E_0}^{\infty} \frac{4\pi J(E)}{E} \sigma(E) \exp(-\tau(E)) \frac{dE}{h}.$$  

In this equation, the radiation field $J(E)$ is described by two power-laws, with differential spectral index $\alpha_\text{ox} = 1.5$ for photon energies between 5 eV and 2 keV and $\alpha_\text{ox} = 0.7$ for higher energies (Crosas and Weisheit, 1993a). (The magnitude of $J(E)$ varies as a function of the radiation luminosity of the AGN, with $L = 10^{45}$ ergs/s being a typical value). The optical depth is defined as

$$\tau(E) = \int_0^r n \sigma_{H,H_e}(E) dr,$$

where $n$ is the density of neutral hydrogen, or neutral or singly ionized helium, and $\sigma(E)$ the corresponding photoionization cross section.

We consider that the narrow line region is formed by clouds with dimensions of $r \sim 10^{14}$ cm, and the density is constant within the cloud (see Figure 4.1). Since the gas is ionized, the neutral hydrogen density is a small fraction ($10^{-3}$) of the total hydrogen density ($10^4$ cm\textsuperscript{-3}). Substituting the values in Eq. 5.16, we find that the optical depth is much less than 1 for all relevant energies.
<table>
<thead>
<tr>
<th></th>
<th><strong>K-Shell</strong></th>
<th><strong>L-Shell</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td>$\sigma = 3.25 \times 10^{-12} E^{-2.77} \text{ cm}^2$</td>
<td>$\sigma = 3.6 \times 10^{-16} E^{-1.64} \text{ cm}^2$</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{Thres}} \simeq 210 \text{ eV}$</td>
<td>$E_{\text{Thres}} = 8.29 \text{ eV}$</td>
</tr>
<tr>
<td>$B^+$</td>
<td>$\sigma = 3.25 \times 10^{-12} E^{-2.77} \text{ cm}^2$</td>
<td>$\sigma = 5.3 \times 10^{-16} E^{-1.7} \text{ cm}^2$</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{Thres}} \simeq 210 \text{ eV}$</td>
<td>$E_{\text{Thres}} = 25.15 \text{ eV}$</td>
</tr>
<tr>
<td>$B^{2+}$</td>
<td>$\sigma = 4.8 \times 10^{-12} E^{-2.82} \text{ cm}^2$</td>
<td>$\sigma = 1.42 \times 10^{-15} E^{-1.99} \text{ cm}^2$</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{Thres}} \simeq 240 \text{ eV}$</td>
<td>$E_{\text{Thres}} = 37.93 \text{ eV}$</td>
</tr>
<tr>
<td>$B^{3+}$</td>
<td>$\sigma = 5.6 \times 10^{-2} E^{-2.84} \text{ cm}^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$E_{\text{Thres}} = 259.38 \text{ eV}$</td>
<td></td>
</tr>
<tr>
<td>$B^{4+}$</td>
<td>$\sigma = 9.9 \times 10^{-12} E^{-3} \text{ cm}^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$E_{\text{Thres}} = 340.21 \text{ eV}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3  Fit to photoionization cross sections of boron
The exponential is then very close to 1 and can be taken out of the integral, using the threshold value for the hydrogen photoionization cross section. The same argument can be applied to helium. Further, since these calculated optical depths are small, the absorptions due to H$^0$, He$^0$ and He$^+$ do not affect much the final boron photoionization rates.

In principle, ionizations are caused not only by radiation from the central source, as has been considered so far, but also by cosmic rays diffusing from the central region out through the narrow line region. In order to estimate their contribution, we first evaluate the ionization rate of hydrogen by cosmic rays and compare this with the photoionization rate. We find that the ionization rate by cosmic rays is four orders of magnitude less than the H$^0$ photoionization rate ($\xi_{H}^{CR} \sim 10^{-9} \text{ s}^{-1}$ compared with $\xi_{H}^{rad} \sim 10^{-5} \text{ s}^{-1}$). To obtain the cosmic ray ionization rate of boron, we can then use the following formula (Weisheit, 1973):

$$\xi_{nl}^{CR} = Q_{nl}(\frac{13.6\text{eV}}{E_{o}(nl)})\xi_{H}^{CR},$$

(5.17)

where $Q_{nl}$ is the number of electrons in the $nl$ subshell with binding energy $E_{o}(nl)$. We find again that, for all cases of interest, cosmic ray ionization of boron is negligible with respect to photoionization.

We also need the total recombination coefficient for each ion. Complex ions such as boron can capture electrons through radiative and dielectronic recombinations. In a dilute plasma recombination to any level is followed by downward radiative transitions, which eventually lead to the ground state. In a dielectronic recombination, the captured electron gives enough energy to the ion to excite one of its bound electrons; the ion ends up in a doubly excited state, and no photon is emitted. Usually, this process reverses itself, but there is a small probability for the doubly excited ion to radiatively decay. This dielectronic recombination sometimes has a rate larger than that of radiative recombination.
Radiative recombination coefficients were obtained in the following way: first, we computed the ground state radiative recombination rate \( \alpha_{if} \) by using the Milne relation (see Osterbrock, 1984, Appendix 1). This relation can be derived by equating photoionization to recombination in local thermodynamic equilibrium,

\[
\alpha_{if} = \frac{\omega_f \sqrt{2} \exp(E_o/kT)}{\omega_i \sqrt{\pi} c^2 (mkT)^{3/2}} \int_{E_o}^{\infty} E^2 \sigma_{fi} \exp(-E/kT) dE .
\]  

(5.18)

Here, \( E_o \) is the ionization potential (or threshold energy), \( k \) is the Boltzmann constant, \( T \) is the temperature (which is 10,000 in our case) \( m \) is the electron mass and \( \omega_i \) and \( \omega_f \) are the statistical weights of the initial and final level, respectively. Since the (ground state) photoionization cross sections \( \sigma_{fi} \) were already fitted to power-laws, the integral in Eq. 5.18 could be solved exactly by evaluating the corresponding incomplete gamma functions. However, if \( E >> kT \) and \( E^2 \sigma_{fi}(E) \) has a much larger value at threshold than at higher energies, then Eq. 5.18 takes the approximation form (Dalgarno and Bates, 1962):

\[
\alpha_{if} = \frac{2.4 \times 10^8 E_o (eV) \omega_f \sigma_{fi}(E_o)}{T^{1/2}(K) \omega_i} \text{ cm}^2 .
\]  

(5.19)

We checked this approximation in some of our cases and we found that the results were essentially the same as those obtained by solving the integral numerically.

Then, we calculated the radiative recombination rates for the excited states by using hydrogenic values, taking into account that \( \alpha(Z,T) = Z \alpha(1,T/Z^2) \), where \( Z \) is the (effective) nuclear charge. (This approximation is seldom accurate for ground states). Since the hydrogenic approximation improves as the excitation of the recombined ion increases, it is reasonable to apply it to all excited state cases. Total radiative recombination rate coefficients (sum of ground state and excited states) are given in Table 5.4 for \( T = 10^4 \) K.

Next, we considered the importance of dielectronic recombinations for some boron ions. Dielectronic recombination coefficients for boron at the temperatures of interest (\( 10^4 \) K) have never been computed. Nevertheless, we can estimate these dielectronic
<table>
<thead>
<tr>
<th>B$^+$</th>
<th>$8.2 \times 10^{-13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B$^{2+}$</td>
<td>$4.8 \times 10^{-12}$</td>
</tr>
<tr>
<td>B$^{3+}$</td>
<td>$7.0 \times 10^{-12}$</td>
</tr>
<tr>
<td>B$^{4+}$</td>
<td>$1.0 \times 10^{-11}$</td>
</tr>
<tr>
<td>B$^{5+}$</td>
<td>$1.9 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

$\alpha_{rad}$ (cm$^3$)

**Table 5.4** Total radiative recombination rate coefficients at $T=10^4$ K.
coefficients by comparing values for other elements which have similar nuclear charge. For high ionization stages, such as \( B^{3+} \) and \( B^{4+} \) (\( B^{5+} \) cannot undergo dielectric recombinations), in which the recombined ion has less than three valence electrons, dielectric recombinations generally are not important (Shull and Van Steenberg, 1982). We extrapolated the values for \( B^+ \) and \( B^{2+} \) from data of C, N and O ions at \( T = 10^4 \) K (Nussbaumer and Storey, 1983; Hahn, 1988), and these are shown in Figure 5.2. In order to check the sensitivity of the results, we estimated from Figure 5.2 an approximate maximum and minimum value for the \( B^+ \) and \( B^{2+} \) dielectric rate coefficients. The final results for the boron ionization states obtained by using the minimum and the maximum value do not differ more than a factor of 2 or 3. This procedure is more precise than extrapolating the Burgess general formula (Burgess, 1964) from its region of validity (\( T > 10^6 \) K) to much lower temperatures (as it is often done in astrophysics). The results obtained by this alternative procedure for C, N and O ions (Shull and Van Steenberg, 1982) are about 2 orders of magnitude less than those obtained by calculations that include the correct transitions at low temperatures (Storey, 1981).

With all the atomic data now in hand, it is possible to obtain the ionization fraction of boron ions in the narrow line region, as a function of the ionization parameter

\[
U = \frac{1}{4\pi R^2 c n_e} \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu, \tag{5.20}
\]

which is just the ionizing photon density divided by the electron density. In Figure 5.3, we plot the calculated relative abundances of \( B^+ \), \( B^{2+} \), \( B^{3+} \) and \( B^{4+} \) for the typical range of ionization parameters corresponding to the narrow line region, which is (Netzer, 1992; Osterbrock, 1991):

\[
0.03 \leq U \leq 10^{-4}. \tag{5.21}
\]

The results reveal that, for \( U = 0.03 \), almost 80% of boron is three times ionized and the rest is half \( B^{2+} \) and half \( B^{4+} \). As expected, the amount of \( B^{2+} \) increases
Figure 5.2 Dielectronic recombination rates coefficients plotted as function of nuclear charge, for recombining ions with different number of electrons (N). The values for $Z_{\text{nucleus}} = 5$ have been extrapolated (thin lines) from the known values for $Z_{\text{nucleus}} = 6, 7, 8$ (thick lines).
Figure 5.3 Ionization structure of boron as a function of ionization parameter
with decreasing ionization parameter. It reaches its maximum (50% of total boron) when \( U \) is about \( 3 \times 10^{-3} \). Then, the B\(^+\) abundance increases and higher ionization state abundances decrease, until almost all the boron becomes singly ionized for the smallest plausible value of \( U = 10^{-4} \). The relative abundance of B\(^{+5}\) is insignificant under narrow line region conditions, and therefore it is not shown in Figure 5.3.

### 5.3 BIII Line Emission

We are particularly interested in B\(^{2+}\) because its strongest emission line, corresponding to the transition \( 1s^2\, 2p \rightarrow 1s^2\, 2s \), is in the ultraviolet, at \( \lambda = 2066 \) Å. This wavelength permits detection by ground-based instruments when the AGN redshift is in the range 0.7 to 2.5. The excited state \( 1s^2\, 2p \) is mainly populated by collisional excitation and depopulated by radiative decay, since the electron density is not very high. Thus, excitation balance between the lower and the upper levels \((a, b)\) can be described by

\[
n_a n_e q_{ab} = n_b A_{ba} \quad ,
\]

where \( A_{ba} = 1.9 \times 10^8 \text{ s}^{-1} \) is the Einstein coefficient for BIII(\( \lambda \)2066), and \( q_{ab} \) is the collisional excitation rate coefficient.

We used the excitation cross section \( \sigma_{ab} \) calculated by Ganas et al. (1983) to determine

\[
q_{ab} = \int_0^\infty vf(v)\sigma_{ab}(v)dv \quad ,
\]

the value of \( v\sigma \) averaged with respect to a Maxwellian distribution of electron velocities,

\[
f(v) = \frac{4}{\pi^{1/2}}\left(\frac{m}{2kT}\right)^{3/2}v^2 \exp\left(-\frac{mv^2}{2kT}\right) \quad .
\]

At \( T = 10^4 \text{ K} \), our computed excitation rate is \( q_{ab} = 2.7 \times 10^{-10} \text{ cm}^3 \text{ s}^{-1} \).

The absolute strength of the (unquenched) BIII line is

\[
j_{ba} = \frac{\hbar \nu}{4\pi} n_b A_{ba} \quad ,
\]

(5.25)
or, using Eq. 5.22,

\[ j_{ba} = \frac{\hbar \nu}{4\pi} n_e n_a q_{ab} \]  \hspace{1cm} (5.26)

However, in order to analyze observed AGN spectra, it is convenient to contrast BIII (\( \lambda = 2066 \AA \)) with some other, nearby line. We chose the CIII] intercombination line because it has a wavelength of \( \lambda = 1909 \AA \) and it is a strong feature in AGN spectra. We used recent data by Steidel and Sargent (1991), who present moderately high-resolution spectra for 92 quasars, in the (rest) wavelength range from \( \lambda \sim 1800 \AA \) to \( \lambda \sim 2800 \AA \). We selected those spectra in which the CIII] line was relatively narrow (e.g., Figure 5.4), and compared the CIII] intensity with that corresponding to any possible feature at 2066\AA. No BIII features could be identified, so in Figure 5.5 we have plotted the upper limits we estimated for the ratio \( j(BIII)/j(CIII) \), whenever this quantity exceeded the value 0.05. Note that there is no discernible trend with respect to redshift.

Finally, in order to relate these observational limits to our spallation calculations, we need an intermediary line, H\( \beta \) = 4861\AA, whose absolute strength can be computed rather easily from the equation

\[ j(H\beta) = \frac{\hbar \nu (H\beta)}{4\pi} n_e^2 \alpha^{eff}(H\beta) \]  \hspace{1cm} (5.27)

where \( \alpha^{eff} \) is an effective recombination rate coefficient tabulated by, e.g., Osterbrock (1984). Here, we assumed that radiative transfer "case B," in which all Lyman line emission is re-absorbed "on-the-spot," is a good approximation for AGN narrow line regions. At \( T = 10^4 \) K, one has, then,

\[ \alpha^{eff}(H\beta) = 3.0 \times 10^{-14} \text{cm}^3\text{s}^{-1}. \]  \hspace{1cm} (5.28)

By using several preceding equations it is easy to show that the abundance of boron relative to hydrogen can now be written as

\[ X(B) = \frac{n_B}{n_H} = \frac{\lambda(BIII) \alpha^{eff}(H\beta) n_B}{\lambda(H\beta) q_{ab}(BIII) n(BIII) j(BIII)} \frac{j(CIII)}{j(H\beta) j(CIII)} \]  \hspace{1cm} (5.29)
Figure 5.4 Spectra shifted into the quasar's rest frame. The observed flux \( f_\nu \) is in \( \mu Jy \) (\( 10^{-29} \) ergs \( s^{-1} \) cm\(^{-2} \) Hz\(^{-1} \)). (Taken from Steidel and Sargent, 1991).
Figure 5.5  Upper limits for the BIII to CIII] ratio obtained from quasar data (Steidel and Sargent, 1991).
Most AGN spectra exhibit NLR ratios of CIII] to Hβ in a narrow range (Netzer, 1992);

\[ 2 \leq \frac{j(CIII)}{j(H\beta)} \leq 8 \quad , \tag{5.30} \]

with 5 being a representative value. Therefore, the boron abundance and the BIII-CIII] line ratio are related according to the following, approximate expression:

\[ X(B) \simeq 2 \times 10^{-4} \left[ \frac{n_B}{n(BIII)} \right] \left[ \frac{j(BIII)}{j(CIII)} \right] \quad . \tag{5.31} \]

This relation, together with our spallation calculations, boron ionization balance results, and estimated line ratio limits, yields an important constraint on AGN cosmic ray fluxes that will be explored in the final chapter.
Chapter 6

IMPLICATIONS AND SPECULATIONS

6.1 Cosmic Ray Flux in AGNs

6.1.1 Limits on Cosmic Ray Fluxes from Boron Data

The upper limit of boron abundance, obtained from observations and analysis of the BIII line, provides information about the maximum amount of cosmic rays that can interact with the narrow line region of AGNs. This upper limit was found in Chapter 5 (Eq. 5.31) to be,

\[ X(B) \leq 2 \times 10^{-4} \left( \frac{n_B}{n(BIII)} \right) \left( \frac{j(BIII)}{j(CIII)} \right). \]

Substituting \( j(BIII)/j(CIII) = 0.05 \), which is a limiting value extracted from the data, and \( n_B/n(BIII) = 0.5 \), which is the value obtained from the boron ionization balance, at the mid-point of the ionization parameter range, yields

\[ X(B) \leq 2 \times 10^{-5} \text{ for } U = 0.002. \]  (6.1)

For the lowest (\( U = 0.0001 \)) and the largest (\( U = 0.03 \)) ionization parameters characteristic of the narrow line region, the upper limit on \( X(B) \) increases because the relative abundance of BIII with respect to B decreases, so

\[ X(B) \leq 1 \times 10^{-4} \text{ for } U = 0.0001 \text{ or } 0.03. \]  (6.2)

At this point, observations can be compared with the theoretical values obtained from the spallation calculation (Table 4.4). The spallation calculation was performed for three different flux-models, and for two diffusion coefficients. In order to make the
comparison, we assumed that the ionization parameter is proportional to the cosmic ray flux. Thus, we can compare the observed value for the lowest ionization parameter with the calculated value for the model with the lowest cosmic ray flux, etc. This is a reasonable assumption if we take into account the correlation suggested in Chapter 3 between the energetics of the system (correlated with the radiation output) and the cosmic ray energy output.

First, a comparison of Model 2 ($L_{CR} = 10^{45}$ ergs/s) with the boron upper limit for the intermediate value of the ionization parameter (Eq. 6.1) shows that the theoretical results for a diffusion coefficient scaled to the NLR ($D_{NLR} = 3 \times 10^{26}$ cm$^2$ s$^{-1}$) disagree with the observations. In fact, the calculated boron abundance for this case varies from $4 \times 10^{-5}$ to $8 \times 10^{-5}$ depending on the metallicity assumed for the AGN gas (i.e., Population II or Population I, respectively). These calculated values are above the $2 \times 10^{-5}$ upper limit. They could only be acceptable if there were a detection of the BIII line that would yield a BIII/C[III] ratio slightly larger than the conservative value of 0.05 used in our analysis. However, the calculated boron abundance obtained from Model 2 with the Galactic diffusion coefficient ($D_{Gal} = 3 \times 10^{28}$ cm$^2$ s$^{-1}$) is in agreement with the observed upper limit. The result in this case varies from $2 \times 10^{-7}$ (for Population II) to $5 \times 10^{-7}$ (for Population I), so it is always well below the upper limit for boron abundance. Even for a case in which the diffusion coefficient had a value between $D_{Gal}$ and $D_{NLR}$ (e.g., $D = 10^{27}$ cm$^2$ s$^{-1}$), this model would still be in complete agreement with the observations.

We then compared Model 1 ($L_{CR} = 10^{44}$ ergs/s) with the observations corresponding to the lowest ionization parameter ($U = 10^{-4}$). The results obtained in all the cases for this model are consistent with the observed upper limit for boron abundance (Eq. 6.2), but in fact are several orders of magnitude lower than this upper limit. This is not a problem as long as there is no actual detection of the BIII emission line, which requires a larger boron abundance. But, because an AGN with low cosmic ray luminosity and low ionization parameter is less likely to show a BIII line in its
spectrum than other AGNs, it might be difficult to confirm the validity of this model: there is less boron formed through spallation (because the cosmic ray flux is low), and there is less BIII resulting from the ionization of boron because the amount of ionizing radiation also is low.

The model with the largest cosmic ray luminosity, Model 3 \((L_{CR} = 10^{46} \text{ ergs/s})\), has the largest amount of boron produced through spallation. This amount of boron is still consistent with the observed upper limit for the largest ionization parameter \((U = 0.03)\), if the diffusion coefficient used in the calculation is \(D_{Gal}\). In this case, the calculated values for boron abundance are \(4.5 \times 10^{-5}\) (Population II) and \(8 \times 10^{-5}\) (Population I), which are both lower than the upper limit, \(X(B) = 1 \times 10^{-4}\). For the other case, in which \(D = D_{NLR} = 3 \times 10^{26} \text{ cm}^2 \text{ s}^{-1}\), the calculated results contradict the observed limit by more than an order of magnitude.

In summary, models with large cosmic ray luminosity \((L_{CR} \approx 10^{46} \text{ ergs/s})\) are acceptable, if the diffusion coefficient is also large, \(D \approx 10^{28} \text{ cm}^2 \text{ s}^{-1}\). Models with an intermediate cosmic ray luminosity \((L_{CR} \approx 10^{45} \text{ ergs/s})\) are acceptable for \(D \geq 10^{27} \text{ cm}^2 \text{ s}^{-1}\). Models with low cosmic ray luminosity are acceptable for any plausible diffusion coefficient. These conclusions are illustrated in Figure 6.1.

If the BIII emission line is detected in future high-resolution AGN spectra, we might be able to identify the model that best reproduces the observed relative strength of the line. Furthermore, if this relative strength is close to the upper limit applied to our analysis \((\text{BIII/CIII]} \approx 0.05)\), then the models most likely to prevail would be those with \(L_{CR} = 10^{45} - 10^{46} \text{ ergs/s}\) and \(D = 10^{27} - 10^{28} \text{ cm}^2 \text{ s}^{-1}\), respectively.

A future application of this work could be a focus on some specific AGNs. If the structure of radio-jets is included, we could study the interaction between the energetic particles and the ionizing gas at the regions where the jet is known to collide with this gas. In fact, there are observations of narrow line emission in some AGNs (e.g. [OIII] in NGC 1068) that overlay the radio emission (Kinney, 1994). We would expect that these interactive regions ("knots") contain substantial amounts of
Figure 6.1 Calculated and observed upper limits for boron abundances as a function of cosmic ray luminosity. Circles represent models with $D_{NLR}$ and squares represent models with $D_{Gal}$. Filled and open symbols correspond to models with Population I and Population II abundances, respectively.
B formed by spallation, which might be detected in a high-resolution spectrum of the object. In this case, we could determine the value of the cosmic ray flux in these regions, and compare it with the values obtained using other observations (γ ray and radio emission). It would be interesting to analyze the spectra of these objects for evidence of light elements.

6.1.2 Effects of Cosmic Rays on BLR clouds

Another important consequence of the existence of cosmic rays in the central region of an active galaxy is their impact on the chemistry of the broad line region (BLR) clouds. In this work, we have concentrated so far on cosmic rays in the more extended narrow line region (NLR), because this is the region of the AGN where spallation is more efficient. However, if these cosmic rays swept through the (inner) BLR before reaching the NLR, then they would affect the physical and chemical state of the gas in the interior of the BLR clouds.

Cosmic rays, unlike ultraviolet radiation, can easily penetrate into the interior of the cloud and heat the gas by ionizing the neutral hydrogen. This heating can be defined by

$$\Gamma^{CR} = \epsilon n_H \xi^{CR} E_e,$$

(6.3)

where $n_H$ is the neutral hydrogen density in the BLR, $\xi^{CR}$ is the cosmic ray ionization rate, $E_e$ is the energy of the electron produced through cosmic ray ionization, and $\epsilon$ is the efficiency with which cosmic rays penetrate the BLR cloud. This efficiency, which is unknown, depends upon the configuration of the magnetic field (Skilling, 1971). In a region where the hydrogen is mostly neutral (as the interior of the BLR cloud), the secondary electrons loose energy in ionizations and excitations. Under these conditions, the remaining free electrons that eventually heat the gas through inelastic collisions have an average energy of $E_e = 10$ eV (Mc Cray and Dalgarno, 1972). The ionization state of the gas in the surface layers of the BLR clouds is unlikely to be changed due to the presence of cosmic rays, since the cross section
is small, of the order of $10^{-20}$ cm$^2$, compare to the H photoionization cross section around threshold ($6 \times 10^{-18}$ cm$^2$). However, deep inside the cloud, the ionization rate due to cosmic rays may be larger than the photoionization rate. This is because most of the low-energy photons (with $E$ near the H and He threshold energy) are absorbed close to the surface of the cloud, and only photons with $E > 1$ keV penetrate inside (e.g., Crosas and Weisheit, 1993a). At these energies, the cross section for H photoionization has actually decreased to $\sim 10^{-23}$ cm$^2$ (Brown, 1971), which gives a very low photoionization rate. Even if cosmic ray ionization is negligible, the heating of the gas by cosmic rays inside the BLR clouds is probably important.

It has been shown in a previous study (Crosas and Weisheit, 1993a) that a transition from atomic to molecular gas can be accomplished at large column densities ($N_H \approx 10^{23}$ cm$^{-2}$) of the BLR cloud. The location of this transition could be modified by heating due to cosmic rays. In the most extreme case, if the gas is heated in large amounts, the formation of molecular hydrogen within BLR clouds, through gas phase reactions, may not be possible at the broad line region. Furthermore, the secondary electrons released by cosmic ray ionization can excite the H$_2$, producing a new generation of UV photons in the interior of the cloud. These photons might destroy other molecules such as CO that could be present in this outer molecular region. But, the actual effect of a large cosmic ray flux in the central region of an AGN must be examined by solving the modified statistical and thermal balances in detail. The effect of the cosmic ray heating in the interior of the BLR cloud can be evaluated by substituting the following values into Eq. 6.3: The density in the BLR cloud is $n = 10^9$ cm$^{-3}$, the ionization due to cosmic rays, for $L_{CR} = 10^{45}$, is $\xi^{CR} = 9 \times 10^{-9}$ s$^{-1}$, and $E_e \approx 10$ eV, as said above. Substitution into Eq. 6.3 gives

$$\Gamma^{CR} \approx \epsilon 10^{-10} \text{ergs cm}^{-3} \text{s}^{-1}.$$  

(6.4)

This can be compared with the heating due to X-rays. The heat deposited into the gas is, in principle, equal to the kinetic energy of the photoelectron (i.e., difference
between initial photon energy and ionization potentials). Helium also plays an important role in the heating due to X-rays, because its photoionization cross sections at high-energies is larger than that for H (Brown, 1971). Then, the actual heat per photon is a mean value obtained from the contribution of both H and He. However, as we said above, for a mostly neutral gas, the secondary electrons lose energy through more ionizations. For example, a 200 eV photon would give a final energy to the gas of about 23 eV (Jura and Dalgarno, 1972). In our case, the X-ray heating deep inside the cloud is caused by photons $E \geq 1$ KeV, which gives $E_e \approx 200$ eV (extrapolating the curves given by Dalgarno and McCray, 1972). The photoionization in this region of the cloud has decreased to $\xi^{X\text{Ray}} \sim 10^{-12}$ s$^{-1}$. Then, the heating is $\Gamma^{X\text{Ray}} \approx 3 \times 10^{-13}$ ergs cm$^{-3}$ s$^{-1}$. This crude calculation confirms the expected importance of cosmic ray heating below the photoionized surface of the BLR cloud.

There are other possible scenarios describing the generation of cosmic rays which need to be considered in this discussion. In these scenarios, the cosmic rays that interact with the NLR might not go through the inner BLR. For example, cosmic rays could be produced by the decay of neutrons which escaped from the active nucleus. This picture has been recently revised by Begelman, de Kool and Sikora (1993), who show that these neutrons could travel across the BLR and eventually be transformed to energetic protons at distances from the center of about 10 pc. Another possibility is that the cosmic rays may diffuse out from the jets into the NLR. This is more likely to occur in the case of AGNs with small, weakly confined jets, so the energetic particles are able to escape (Niemeyer and Bierman, 1994). In this situation, cosmic rays do not interact much with the BLR, since the jet is more confined in this inner region and particles cannot readily escape.

Improved observations may help our understanding of the origin of energetic particles in AGNs, and provide enough information to determine which - if any - scenario is correct. It is also possible that different situations coexist, so that the complexity of the problem is even greater. In any of these cases, investigation of the physical and
chemical conditions of the BLR gas becomes an important way to clarify these other aspects of the global AGN picture.

6.2 Implications for the Build-Up of Light Elements

In this work (Chapters 4 and 5), we have showed how the production of light elements through spallation can set upper limits on cosmic ray fluxes in AGNs. In addition, the formation of light elements is important in itself for understanding some aspects of chemical evolution. In this section we discuss the relevance of our work (applied so far to AGNs) to the enrichment of light elements in "normal" galaxies, including our own Milky Way.

6.2.1 Active Phase in "Normal" Galaxies

Studies on the space density of extragalactic objects suggest a large fraction of present normal galaxies might be associated with quasars (Begelman, Blandford, and Rees, 1984). In fact, the space density of quasars is very close to that of normal galaxies ($\sim 10^7$ objects per cubic Hubble radius). Based on this same argument, it has also been suggested that our Galaxy was a Seyfert galaxy in an early epoch, with a black hole of $\sim 10^6 M_\odot$ in its center (Bailey and Clube, 1978; Riegler and Blanford, 1982). Studies on the kinematics of gas and stars in the Galactic center are consistent with the existence of a compact object with this mass (Genzel and Tormes, 1987).

During an active phase ($T_{AGN} \sim 10^8$ years) of its the history, our Galaxy would emit radiation, from accreting material, proportional to the mass of the black hole (see Chapter 3, Eq. 3.2),

$$L \approx L_E = 3 \times 10^{46} M_8 = 3 \times 10^{44} \text{ergs s}^{-1} \ .$$

(6.5)

This radiation luminosity is likely to be also proportional to the amount of cosmic rays originating in the nucleus. If we assume that the cosmic ray luminosity is not greater than 1/100 of the total radiation luminosity, we get $L_{CR} \leq 10^{42}$ ergs s$^{-1}$. 
This amount of cosmic rays interacting with the ionized gas in the center of our early Galaxy could have had an impact on the formation of Galactic light elements. Before exploring this issue, we first review the observed abundances of light elements in the Milky Way.

### 6.2.2 Light Element Abundances

#### Primordial Abundances

The amount of Li and D formed in the Big Bang is a function of the baryon density, $\rho_b$, in the present universe (Wagoner, 1973). This baryon density determines the evolution of the universe in the following way: if $\rho_b$ is smaller than the critical baryon density,

$$\rho_c = 1.9 \times 10^{-29} h_0^2 \text{ gcm}^{-3},$$  \hspace{1cm} (6.6)

where $h_0$ is the present Hubble constant in units of 100 Km s$^{-1}$ Mpc$^{-1}$, then Friedmann models predict that the universe is open. If $\rho_b$ is larger than $\rho_c$, the universe is closed. The dependence between primordial Li and D abundances and $\rho_b$ is shown in Figure 6.2 (taken from Wagoner, 1973), in which the values are obtained from the standard Big Bang nucleosynthesis scenario. Figure 6.2 also shows how the primordial Li and D abundances relate to each other, so if one of the abundances is determined, the other abundance must satisfy the ratio given by the curves from the plot, in order to not contradict standard nucleosynthesis.

A lot of effort has been put into observing Li and D in our Galaxy, and then inferring the primordial abundances of these elements. It has been found that the deuterium abundance in the solar system is $D/H = 2 \pm 1 \times 10^{-5}$, and that in the general interstellar medium it is $D/H = 1.5 \pm 0.5 \times 10^{-5}$ (Audouze, 1981). Furthermore, it is believed that D can only be destroyed, and not synthesized, in the course of stellar evolution. So, the primordial D abundance should be larger than $10^{-5}$, unless the gas from the regions where deuterium is detected is renewed through some, very
Figure 6.2 Standard Big Bang nucleosynthesis as a function of baryon density, taken from Wagoner (1973).
hypothetical, process of accretion of primordial matter (Audouze and Tinsley, 1974).  

$^7$Li observations are available for Galactic disk stars (Population I) and for halo stars (Population II) (Audouze, 1981; Spite and Spite, 1982). The $^7$Li abundance in the Galactic disk is $^7$Li/H = $10^{-9}$ and in the halo it is $^7$Li/H = $10^{-10}$. It was first thought that the lithium found in halo stars had been depleted, so the primordial value for $^7$Li/H could be much larger than $10^{-10}$ (and it was assumed to be the Galactic disk value). But, extensive studies (e.g., Deliyannis et al., 1989) were performed later to try to find any evidence for depletion, and the result was negative. They were able to claim that $^7$Li in halo stars was undepleted because the abundance of $^7$Li did not change with the effective temperature of these stars. In case of depletion, different types of stars would have had to destroy exactly the same amount of $^7$Li, which seemed very unlikely.

Therefore, it is now believed that the primordial value for $^7$Li/H is $10^{-10}$, i.e., the value found in the (undepleted) halo stars. From Figure 6.2, it follows that the corresponding primordial value for D/H is $10^{-4}$. These values are the solution (from standard Big Bang nucleosynthesis) for a universe with $\rho_b \approx 3 \times 10^{-31}$ g cm$^{-3}$, much lower than the critical baryon density $\rho_c$ needed for closure. The large amount of primordial D allows for its destruction in stellar evolution, so it is consistent with the observed D/H = $10^{-5}$ mentioned above. However, in order for the primordial $^7$Li to agree with the value $^7$Li/H = $10^{-9}$ observed in the interstellar medium, one needs to produce significant amounts of $^7$Li during Galactic evolution. In principle, this production can be done either through spallation by cosmic rays or in stellar evolution. The present cosmic ray flux in the Galaxy is not sufficient to reproduce the observed $^7$Li abundance through steady build-up (Meneguzzi, Audouze and Reeves, 1971), and $^7$Li production in the interior of the stars is, although still uncertain, likely to be inefficient.
Disk and Halo Abundances for Be B

The observed abundances in the ISM are $B/H = 3 \times 10^{-10}$ and $B/\text{He} = 2 \times 10^{-11}$ (Prantzos, Casse and Vangioni-Flam, 1993). It is believed that spallation by the present cosmic ray flux in the Galaxy, operating over its entire history, dominates the formation of these elements.

Recent observations of Be and B in old halo stars (Gilmore et al, 1991, 1992; Duncan et al, 1992) show that $B/\text{He} \approx 1.5 \times 10^{-13}$ there (Population II), and the B/Be ratio is about 10. This ratio is reproduced naturally by cosmic ray spallation.

6.2.3 Effect of an Active Phase on the Light Element Abundances

In order to evaluate the contribution to Galactic chemical evolution of light elements produced during an active phase, we compare the mass of light elements spalled in the active phase with the mass of light elements now in the inner halo and in the disk:

\begin{align*}
\mathcal{L}(M_\odot)_\text{AGN} &= 5 \times 10^6 A(\mathcal{L}/H)_\text{AGN} \\
\mathcal{L}(M_\odot)_\text{Halo} &= 1.4 \times 10^{10} A(\mathcal{L}/H)_\text{Halo} \\
\mathcal{L}(M_\odot)_\text{Disk} &= 6 \times 10^{10} A(\mathcal{L}/H)_\text{Disk}
\end{align*}

In these equations, $\mathcal{L}$ corresponds to any light element, $A$ is its atomic mass number, and $(\mathcal{L}/H)$ is its relative abundance. The total mass of the inner halo is the sum of the the core ($1.1 \times 10^{10} M_\odot$) and the spheroid ($0.27 \times 10^{10} M_\odot$) masses (Bahcall, Schmidt and Soneira, 1983); Freeman (1987) estimates that the total mass of the disk is $6 \times 10^{10} M_\odot$. The total mass of the gas in the active region we take to be the mass associated with the narrow line region of a typical AGN, with a radius of 100 pc, and $n = 10^4 \text{ cm}^{-3}$, and $f = 10^{-2}$ (see Chapter 4).
We first compare the halo abundances with the the abundances obtained during the AGN phase:

\[
\frac{L(M_\odot)_{\text{AGN}}}{L(M_\odot)_{\text{Halo}}} = 3 \times 10^{-4} \frac{(L/H)_{\text{AGN}}}{(L/H)_{\text{Halo}}}. \tag{6.10}
\]

If \( L(M_\odot)_{\text{AGN}} / L(M_\odot)_{\text{Halo}} \sim 1 \), then the active phase will be able to produce the observed halo abundances of light elements. This is so for a cosmic ray luminosity (during the active phase) of about \( 10^{41} \) ergs s\(^{-1}\), a luminosity that is consistent with the upper limit obtained from having only a \( 10^6 M_\odot \) black hole in the center of our Galaxy. For this explanation to be true, the AGN phase would have had to occur very early in the history of the Galaxy, plus, the central (AGN) gas would have had to mix promptly and efficiently with the gas already in the halo.

However, to reproduce the disk abundances during the active phase, the cosmic ray luminosity required is \( L_{CR} \geq 10^{43} \) ergs s\(^{-1}\). This is above the upper limit set by the black hole mass. By using the maximum cosmic ray luminosity allowed, \( L_{CR} \approx 10^{42} \) ergs/s, we find that the maximum contribution of an active phase to the observed disk abundances is between 10% and 20%. This build-up also could occur in a different scenario, in which the AGN was formed after the halo, but the central gas still would need to become mixed with the gas in the disk in a time scale less than \( 10^{10} \) yr in order to distribute the light elements through out the whole Galaxy.

This active phase model can also be applied to other galaxies which might harbor a black hole in their centers. In fact, stellar-kinematic measurements show that several galaxies, e.g., M31, NGC 3115, M32, NGC 4594 and NGC 3115, each must have a central compact object of mass between \( 10^7 \) and \( 10^9 M_\odot \) (Kormendy, 1991). Recent work based on the detection of strong iron emissions in high-redshift quasars (Elston, Thompson and Hill, 1994) also supports the idea that quasars promptly enrich the center of massive galaxies. We believe that the nucleosynthesis consequences of an active phase during a galaxy’s past deserve to be investigated in more detail. Indeed this might be an important aspect of the build-up of light element abundances, and it may even help in identifying some “normal” galaxies that once had active nuclei.
REFERENCES

Audouze, J. 1986 “Nucleosynthesis and Chemical Evolution” (Eds. B. hauck, A.
Maeder, G. Meynet)
Energetic Cosmic Rays” (Eds. M. Nagano & F. Takahara)
Baldwin, J., Boksenberg, A., Burbidge, R. Carswell, R., Cowsik, R., Perry, J. &
Bechtold, J. et al. 1994 (in preparation)
56, No. 2, Part I, 255
Energetic Cosmic Rays” (Eds. M. Nagano & F. Takahara)
Blandford, R. D., Netzer, H. & 1990, “Active Galactic Nuclei” (Springer-Verlag)
Crosas, M. & Weisheit, J. C. 1993b, Revista Mexicana de Astronomía y Astrofísica, 27, 107
Ginzburg, V. L. 1989, "Applications of Electrodynamics in Theoretical Physics and Astrophysics" (Gordon and Breach Science Publishers)
Hahn, Y. 1988, Physica Scripta, T28, 24
Krolik, J.& Begelman, M. C. 1988, 324, 714
Laing, R. A. 1982, IAU Symposium 97, “Extragalactic Radio Sources” (Eds. D. S.
Heeschen & C. M. Wade)
Protheroe, R. J. & Kazanas, D. 1983, Proceedings of the NATO Advanced Study
Institute, “Composition and Origin of Cosmic Rays” (Ed. M. M. Shapiro)
Read, S. M. & Viola, V. E. 1984, Atomic Data and Nuclear Data Tables, 31, 359


Shull, J. M. & Van Steenberg, M. V. 1982, 48, 95


Stecker, 1971, "Cosmic Gamma Rays", NASA Scientific and Technical Information, Office NASA SP-249


Takahara, F. 1990, Prog. Theor. Phys., Vol. 31, No. 6


Weinberg, S. 11972, "Gravitation and Cosmology" (Wiley, New York)

Weise, Smith & Gleimer, 1966


Zatsepin, G. T. & Kuz'min, V. A. 1966, ZhETF Pis'ma, 4, No. 3, 114
Appendix A

First Order Fermi Acceleration

First order Fermi acceleration is thought to be the main mechanism through which cosmic rays are accelerated. It is based on the idea that particles can gain energy when they bounce off a "wall" or "mirror" which is moving toward them. If the particles have initially energy $E_0$ and momentum $p_0$ in the lab frame, and the mirror is moving at velocity $V$, then in the rest frame of the mirror, the particle energy and momentum are

\[ E' = \gamma V \left( E_0 + V p_0 \right) \]  \hspace{1cm} (A.1)

\[ p' = \gamma \left( p_0 + \frac{V E_0}{c^2} \right) \]  \hspace{1cm} (A.2)

where

\[ \gamma = \frac{1}{\sqrt{1 - V^2/c^2}} \]  \hspace{1cm} (A.3)

After the collision, the particle momentum $p'$ becomes $-p'$, and the energy $E'$ is conserved in the mirror rest frame. To find the final energy $E_1$, we transform $E'$ to the lab frame again,

\[ E_1 = \gamma (E' + V p') \]  \hspace{1cm} (A.4)

Then, we substitute $E'$ and $p'$

\[ E_1 = \gamma^2 \left( E_0 + 2 V p_0 + \frac{V^2}{c^2} E_0 \right) \]  \hspace{1cm} (A.5)

and use the definition of $\gamma$ (Eq. A.3) to express $E'$ in the following way:

\[ E_1 = \gamma^2 \left( \frac{E_0}{\gamma V} + 2 \frac{V^2}{2} c^2 E_0 + 2 V p_0 \right) \]  \hspace{1cm} (A.6)

\[ E_1 = E_0 2 \gamma V \frac{V}{c} \left( \frac{V}{c} + \frac{p_0 c}{E_0} \right) \]  \hspace{1cm} (A.7)
Finally, by using the relations $E_0 = \gamma_0 mc^2$ and $p_0 = \gamma_0 mv$, we can substitute the last term $p_0 c/E_0$ from Eq. A.7 by $v/c$. Then, the difference between final and initial energy reduces to

$$\Delta E = E_1 - E_0 = 2\gamma^2 E_0 \left( \frac{V}{c} + \frac{v}{c} \right).$$

(A.8)

The velocity of the particles $v$ is much larger than the mirror velocity $V$, so $V/c$ can be neglected in the sum. Thus, the energy gain after one "head-on" encounter with the mirror is proportional to $V/c$:

$$\frac{\Delta E_0}{E_0} = O\left( \frac{V}{c} \right).$$

(A.9)

This is the reason why this Fermi mechanism is called first order.

It has been shown that this process can occur in strong shocks (Bell, 1978; Blandford and Ostriker, 1978). In this particular case, the gas behind the shock behaves as the mirror, and the velocity $V$ corresponds to the relative velocity of the shocked gas with respect to the unshocked gas. The particles are considered to be isotropically distributed at each side of the shock, due to the large number of scatterings produced by Alven waves. Some of the particles will recross the shock and reach isotropy again, and others will be mixed with the gas behind the shock (downstream) after crossing. Thus, only those particles which go back and forth across the shock gain some energy (Eq. A.9).

The distribution $N$ of these accelerated particles as a function of energy $E$ after many "head-on" collisions can be found using the following general argument (Longair, 1981). We first define $\beta$ as the ratio between the energy after and before a "collision" with the shock. We define $P$ as the probability that a particle stays in the acceleration region after a collison, so $1 - P$ is the probability of escaping after a collision. Then, after $k$ collisions,

$$E = E_0 \beta^k$$

(A.10)

$$N = N_0 P^k$$

(A.11)
From these equations, we can derive the relation
\[
\frac{\ln(N/N_0)}{\ln(E/E_0)} = \frac{\ln P}{\ln \beta},
\]  
(A.12)
and it follows,
\[
\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\ln P/\ln \beta}.
\]  
(A.13)
Hence, we eventually obtain a power law energy spectrum,
\[
dN(E) = E^{(\ln P/\ln \beta - 1)} dE.
\]  
(A.14)

Now \(P\) and \(\beta\) can be evaluated for the case of a shock, applying the same procedure used by Bell (1978): It has been shown above (Eq. A.7) that the energy gain in an encounter perpendicular to the shock is approximately
\[
\frac{\Delta E}{E} \approx 2 \frac{V}{c}.
\]  
(A.15)
If we average over all angles in which cosmic rays can encounter the shock (i.e. we consider the projection of an isotropic flux into a plane), we obtain
\[
\frac{\Delta E}{E} = \frac{4}{3} \frac{V}{c}.
\]  
(A.16)
Thus, since \(\beta\) was defined as the ratio between the energy of the particle after and before colliding with the shock, we find that
\[
\beta = 1 + \frac{4}{3} \frac{V}{c}.
\]  
(A.17)
We can also define \(P\) as:
\[
P = \frac{F_1 - F_2}{F_1},
\]  
(A.18)
where \(F_1\) is the flux of particles that encounter the shock and \(F_2\) is the flux of particles downstream \(F_2\) after crossing the shock. So, \(F_1\) and \(F_2\) can be expressed as:
\[
F_1 = n_1 v \frac{1}{2} \int_0^1 \mu d\mu,
\]  
(A.19)
where $n_1$ is the number density of particles that cross the shock from upstream, $v$ is the cosmic ray velocity, and $\mu = \cos \theta$. After integration,

$$F_1 = n_1 \frac{v}{4} \ .$$  \hspace{1cm} (A.20)

And

$$F_2 = n_2 u_2 \ ,$$  \hspace{1cm} (A.21)

where $n_2$ is the number density of particles that are mixed with the downstream after crossing, and $u_2$ is the downstream velocity. Then, we substitute Eqs. A.19 and A.20 into the definition of $P$,

$$P = \frac{n_1 v/4 - n_2 u_2}{n_1 v/4} \ .$$  \hspace{1cm} (A.22)

If we consider that the number of cosmic rays is not modified much by the shock, then $n_1 \approx n_2$, and $P$ for relativistic particles simplifies to

$$P = 1 - \frac{4u_2}{c} \ .$$  \hspace{1cm} (A.23)

Finally, we can apply these results to the general expression for the cosmic ray distribution (Eq. A.14). First, we take logarithms of $\beta$ and $P$ and expand them. Since both $V$ and $u_2$ are much smaller than $c$, we can neglect the second order terms, that is,

$$\ln \beta = \frac{4V}{3c} \ ,$$  \hspace{1cm} (A.24)

$$\ln P = -\frac{4u_2}{c} \ .$$  \hspace{1cm} (A.25)

Then, we divide Eq. A.25 by A.24,

$$\frac{\ln P}{\ln \beta} = -3u_2 \frac{1}{V} = \frac{3u_2}{u_1 - u_2} \ ,$$  \hspace{1cm} (A.26)

and use the definition of the compression ratio $r = u_1/u_2$ to obtain

$$\frac{\ln P}{\ln \beta} = \frac{3}{r - 1} \ .$$  \hspace{1cm} (A.27)
Therefore, the power law energy spectrum becomes

\[
\frac{dN}{dE} = kE^{-(1+3/(r-1))}.
\]  
(A.28)

We have recovered the power law introduced in Eq. 1.6, where the spectral index was expressed as,

\[
dN(E) \propto E^{-\alpha} \text{ with } \alpha = (r + 2)/(r - 1).
\]

We can also relate \( r \) to the Mach number \( M \),

\[
r = \frac{(\gamma + 1)M^2}{(\gamma - 1)(M^2 + 2)},
\]  
(A.29)

and express \( \alpha \) in terms of \( M \),

\[
\alpha = \frac{2(M^2 + 1)}{(M^2 - 1)}.
\]  
(A.30)

Thus, for strong shocks, as \( M \to \infty \), \( \alpha \) becomes 2. In order to obtain the observed cosmic ray spectrum at low energies, for which \( \alpha \sim 2.6 - 2.7 \), \( M \) needs to be approximately \( 2.6 - 2.8 \).
Appendix B

FORTRAN Programs

B.1 Propagation of Cosmic Rays from Quasars to Earth

This FORTRAN program evaluates the flux of cosmic rays escaping from quasars received on earth, by applying Eqs. 2.13 and 2.14. The input file defines the values of the following variables: the cosmic ray luminosity at each quasar, the differential spectral index $\alpha$ of the power-law that describes the quasar cosmic ray flux, the maximum energy for the cosmic rays emanating from the quasars, the evolution parameter $m$ introduced in Eq. 2.18, and the maximum redshift considered in the integration of the quasar cosmic ray flux over quasar evolution.

```
c23456******* Observed and Calculated Cosmic Ray Flux *******

double precision fo(79),fc(79),ev(79),der,crl,r,c,coff,pi,a1,
u a2,b,pfo(79),pfc(79),emin

pi=3.1415926535

c=2.99d8

Flux at 5.e15 eV (part/eV m^-2 s sr)

a1=6.d-23

Flux at 1.e19 eV (part/eV m^-2 s sr)

a2=3.d-33
```
Minimum Energy for cosmic rays escaped from quasars
emin=1.d17

Hubble Radius (m)
h=100.
r=c/3.24d-18*(100./h)

Density of quasars
den=1.d5/r**3

Variables
write (6,*) 'Cosmic Ray Luminosity (Ergs/s)'
read (8,*) crl
write (6,*) crl
write (6,*) 'Spectral Index'
read (8,*) alpha
write (6,*) alpha
write (6,*) 'Energy cutoff (eV)'
read (8,*) coff
write (6,*) coff
write (6,*) 'Evolution Parameter'
read (8,*) pm
write (6,*) pm
write (6,*) 'Maximum Redshift'
read (8,*) zmax
write (6,*) zmax

open (1,file='ev.d1',status='old')
do 1 i=1,79
read (1,*) ev(i)

Observed Flux
if (ev(i).gt.1.d19) then
  fo(i)=a2*(1.d19/ev(i))**2.2
elseif (ev(i).gt.1.d17) then
  fo(i)=a2*(1.d19/ev(i))**3.2
elseif (ev(i).gt.5.d15) then
  fo(i)=a1*(5.d15/ev(i))**3.0
elseif (ev(i).ge.1.d9) then
  fo(i)=a1*(5.d15/ev(i))**2.7
endif

Calculated Flux
if (alpha .eq. 2.) b=crl/(4.*pi*(1.d19)**alpha*23.*1.6d-12)
if (alpha .gt. 2.) b=crl/(4.*pi*(1.d19)**alpha*
  u(1.d19**((2.-alpha)-1.d9**((2.-alpha))/(2.-alpha)*1.6d-12))
if (alpha .lt. 2.) b=crl/(4.*pi*(1.d19)**alpha*
  u(1.d19**((2.-alpha)-1.d9**((2.-alpha))/(2.-alpha)*1.6d-12))
if (ev(i).le.coff/((1.+zmax)**2.) .and. ev(i).ge.emin/(1.+zmax))
  then
    fc(i)=3./(8.*pi)*den*r*b*(1.d19/((1.+zmax)*ev(i)))**alpha*(((1.
    u+zmax)**(pm-alpha-0.5)-1.)/(pm-alpha-0.5))
  endif
if (ev(i) .gt. coff/((1.+zmax)**2.) .and. ev(i) .lt. coff) then
  fc(i)=3./(8.*pi)*den*r*b*(1.d19/((1.+zmax)*ev(i)))**alpha*(((coff
  u/ev(i))**(0.5*(pm-alpha-0.5))-1.)/(pm-alpha-0.5))
endif
if (ev(i) .lt. emin/(1.+zmax)) fc(i)=1.d-40/(ev(i)**2.)
if (ev(i) .ge. coff) fc(i)=1.d-40/(ev(i)**2.)

pfo(i)=fo(i)*ev(i)**2.
pfc(i)=fc(i)*ev(i)**2.
write (6,99999) ev(i),pfo(i),pfc(i)
1 continue

99999 format (1x,e10.2,e12.3,e12.3)

end
B.2 Diffusion and Spallation of Cosmic Rays in the Narrow Line Region

The following program calculates the cosmic ray density in an AGN, after the cosmic rays have diffused out from the central region. This density is obtained as a function of time and distance from the source by evaluating Eq. 3.12. Then, it calculates the flux of cosmic rays in the narrow line region after undergoing ionization losses. In order to do this, the integral in Eq. 3.19 is solved numerically by using the subroutine D01AMF from the NAG fortran library. This subroutine applies the Gauss 7-point and Kronrod 15-point rules to the integral, after it has been transformed to a new integral with integration range from 0 to 1. The resulting flux is used to compute the production of Li, Be and B through spallation (Eq. 3.20). The spallation cross section needed to perform this calculation are taken from the seven files given in Appendix C. The final results are in the form of ratios between the isotopes \( ^{6}\text{Li}, ^{7}\text{Li}, ^{9}\text{Li}, ^{9}\text{Be}, ^{10}\text{B}\) and hydrogen abundances.

c************************** Diffusion / Spallation Program **********

c
This program computes the distribution of cosmic rays by using a diffusion model. Then, it calculates the equilibrium spectrum of this cosmic rays, when energy losses are included. Finally, it computes the abundance of light elements produced by spallation, when the equilibrium spectrum interacts with the nuclei from the NLR

c implicit double precision (a-h,o-z)
double precision dc,t(14),r,p,rf,qo,dens
double precision ion,flux(46),ev(46),ri,
* gaus(29), dis(29), erfc(29), dist(29), ty(29),
* ff, tau, alpha, lam, po, erfci(29), rpc, disti(29),
* a, abserr, epsabs, epsrel, result, evm(29),
* erfc2(29), erfci2(29), er(29), eri(29), q(46)
  double precision cs(19, 5, 5, 8), ple(8), ptle(8),
* evs(19), sflux(19, 5),
* xnlr(5), fluxs(19), tflux(46, 5), flurt(46),
* evt(46), xle(8), xfl(5),
* tin(46, 5, 5, 8), sin(19, 5, 5, 8)

integer mod, le

c Subroutines Parameters
integer lw, liw
parameter (lw=800, liw=lw/4)
integer nout
parameter (nout=6)

c Scalars
integer kount
integer ifail, inf

c Arrays
real*8 w(lw)
integer iw(liw)

c External Functions
external fst

c External Subroutines
external d0lamf

c Common Blocks
common /telnum/kount
common /lower/ilimit
common /lamda/lam, alpha, ion

C Constants (cgs)
pi=3.14e0
c=3.e10

C *********** Distribution of Cosmic Rays ***********
C Apply pure diffusion model to narrow line region in AGNs
C The model describes a central source that starts to inject
C particles at t=0. The final distribution has been integrated
C over time and position.
C dist: final distribution (as a function of time)
C dis: final distribution (as a function of position)
C gaus: Distribution for injection only at t=0.
C dc: Diffusion Coefficient (cm^-2 s^-1)
C filling factor for NLR
ff=1.e-2
C density of NLR (g cm^-3)
dens=1.6e-20
C r at 100pc and at 10pc
rf=3.d20
ri=3.d19
C Production Rate 'p'(part s^-1)
open (7, file='crinput', status='old')
write (6,*) 'Model'
read (7,*) mod
write (6,*) mod
if (mod.eq.1) then
  alpha=1.7e0
po=3.7d49
end if
if (mod.eq.2) then
  alpha=2.e0
  po=2.7d55
end if
if (mod.eq.3) then
  alpha=2.3e0
  po=9.3d59
end if
p=p0*(1.e-7)**(alpha-1)/(alpha-1)

open (8,file='dfinput')
write (6,*) 'Diffusion Coefficient'
read (8,*) dc
write (6,999999) dc

open (1,file='diff.d',status='old')
do 1 l=1,29
  read (1,*) t(l),erfc(l),erfci(l),erfc2(l),
  *      erfci2(l)
1 continue
do 2 r=-3.d20,3.d20,1.d19
  do 3 j=1,29
    gaus(j)=p/((4.*pi*dc*t(j))**1.5)*exp(-1.*r**r/
    * (4.*t(j)*dc))
    dis(j)=p/(4.*pi*dc*abs(r))*(1.-2./pi**0.5*(abs(r)
    * /((4.*dc*t(j))**0.5)-abs(r)**3/(3.*(4.*dc*t(j))**
* 1.5))
  if (dis(i).le.1.d-50) dis(i)=1.d-50
  if (dc.eq.3.0d28) then
    er(j)=erfc(j)
    eri(j)=erfci(j)
  end if
  if (dc.eq.3.0d26) then
    er(j)=erfc2(j)
    eri(j)=erfci2(j)
  end if
  dist(j)=p/(4.*pi*dc*rf)*er(j)
  disti(j)=p/(4.*pi*dc*ri)*eri(j)
  if (dist(i).le.1.d-50) dist(i)=1.d-50
  if (disti(i).le.1.d-50) disti(i)=1.d-50
3 continue
  rpc=r/3.d18
  write (6,99998) rpc,dis(16),dis(19),dis(22),dis(24)
2 continue
  do 4 k=1,29
    ty(k)=t(k)/(pi*1.e7)
  c write (6,99997) ty(k), dist(k), disti(k)
4 continue

c  ************* Equilibrium Cosmic Ray Spectrum *************
c  Use the diffusion-loss equation to find the equilibrium cosmic
c  ray spectrum. The terms considered are the single source, the
c  diffusion term and the energy loss term. The gradient of cosmic
c  rays is considered negligible, so dF/dX is zero, and the final
spectrum only depends on energy.
lam: Escape path length
q: central source
tau: Escaping time

Ionization Losses (eV cm^-2 g^-1), in fully ionized plasma
ion=9.3e6

tau=rf**2/dc
lam=dens*ff*c*tau
qo=poc*rf/(dc*dens*ff*4./3.*pi*rf**3)

open (2, file='ev.d2', status='old')
open (20, file='flux.r', status='unknown')
do 5 i=1,46

set lower limit value

ilimit=i
read (2,*) ev(i)

Subroutine to integrate the cosmic ray flux over energy
(en), from a specific energy ev(i) to infinity.
set limits of integration
a=ev(i)
inf=1

set error tolerances
epsabs=1.0e0
epsrel=1.0e-3
kout=0
ifail=-1
call d01amf(fst,a,inf,epsabs,epsrel,result,abserr,w,
+ lw,iw,liw,ifail)
flux(i)=qo/ion*result
if (flux(i).le.1.d-50) flux(i)=1.d-50
q(i)=po*c/(4.*pi*dcrf)*ev(i)**(-1.*alpha)
if (q(i).le.1.d-50) q(i)=1.d-50
evm(i)=ev(i)/1.e6

c print results
write (nout,*)
if (ifail.ne.0) write (nout,99996) 'ifail=',ifail
if (ifail.le.5) then
write (20,99995) ev(i),flux(i)
endif

c write (nout,99993) ev(i),flux(i),q(i)
5 continue

c

********** Spallation Products **********
c Use the spallation equation (experimental cross sections
c multiplied by the equilibrium cosmic ray flux) to obtain
c the abundances of light elements formed in the NLR.
c First: Interaction between C,N and O from NLR gas and
c H and He from cosmic rays. In this case, the resulting
c Li, Be and B have low energies.
c
open (11,file='cs.1', status='old')
open (12,file='cs.2', status='old')
open (13,file='cs.3', status='old')
open (14,file='cs.4', status='old')
open (15,file='cs.5', status='old')
open (16,file='cs.6', status='old')
open (17,file='cs.7', status='old')
rewind (20)
do 6 ii=1,19

c     Read cross sections for E < 1000 MeV
    read (11,*) evs(ii),cs(ii,1,3,1),cs(ii,1,3,2),
         *     cs(ii,1,3,3),cs(ii,1,3,4),cs(ii,1,3,5),
         *     cs(ii,1,3,6),cs(ii,1,3,7),cs(ii,1,3,8)
    read (12,*) evs(ii),cs(ii,1,4,1),cs(ii,1,4,4),
         *     cs(ii,1,4,5),cs(ii,1,4,6),cs(ii,1,4,7)
    read (13,*) evs(ii),cs(ii,1,5,1),cs(ii,1,5,2),
         *     cs(ii,1,5,3),cs(ii,1,5,4),cs(ii,1,5,5),
         *     cs(ii,1,5,6),cs(ii,1,5,7),cs(ii,1,5,8)
    read (14,*) evs(ii),cs(ii,2,2,1),cs(ii,2,2,2),
         *     cs(ii,2,2,4)
    read (15,*) evs(ii),cs(ii,2,3,1),cs(ii,2,3,2),
         *     cs(ii,2,3,4),cs(ii,2,3,5),cs(ii,2,3,6),
         *     cs(ii,2,3,7),cs(ii,2,3,8)
    read (16,*) evs(ii),cs(ii,2,4,1),cs(ii,2,4,2),
         *     cs(ii,2,4,4),cs(ii,2,4,5),cs(ii,2,4,6),
         *     cs(ii,2,4,7),cs(ii,2,4,8)
    read (17,*) evs(ii),cs(ii,2,5,1),cs(ii,2,5,2),
         *     cs(ii,2,5,4),cs(ii,2,5,5),cs(ii,2,5,6),
         *     cs(ii,2,5,7),cs(ii,2,5,8)
read (20,*) evs(ii),fluxs(ii)
cs(ii,1,4,2)=0.0
cs(ii,1,4,3)=0.0
cs(ii,1,4,8)=0.0
cs(ii,2,2,3)=0.0
cs(ii,2,2,5)=0.0
cs(ii,2,2,6)=0.0
cs(ii,2,2,7)=0.0
cs(ii,2,2,8)=0.0
cs(ii,2,3,3)=0.0
cs(ii,2,4,3)=0.0
cs(ii,2,5,3)=0.0
do 7 le=1,8
  cs(ii,1,1,le)=0.0
  cs(ii,1,2,le)=0.0
  cs(ii,3,3,le)=0.0
  cs(ii,3,4,le)=0.0
  cs(ii,3,5,le)=0.0
  cs(ii,4,4,le)=0.0
  cs(ii,4,5,le)=0.0
  cs(ii,5,5,le)=0.0

Fraction of H,He,C,N and O in the CR Flux
xfl(1)=0.9
xfl(2)=0.09
xfl(3)=3.35e-4
xfl(4)=1.03e-4
xfl(5)=6.06e-4

Abundances of H,He,C,N and O in the NLR (wrt H)
xn1r(1)=1.0
xn1r(2)=0.1
xn1r(3)=3.72e-6
xn1r(4)=1.15e-6
xn1r(5)=6.74e-6

/* H, He, C, N and O Cosmic Ray Flux */
do 8 m=1,5
do 9 n=1,5
   sflux(ii,m)=xfl(m)*fluxs(ii)
   cs(ii,n,m,le)=cs(ii,m,n,le)
9  continue
8  continue
7  continue
6 continue
do 10 le=1,8
   ple(le)=0.0
do 11 ie=1,18
do 12 m=1,5
   if (m.le.2) esc=1.0
   if (m.ge.3) then
      if (evs(ie).gt.(ion*lam)) esc=0.0
      if (evs(ie).le.(ion*lam)) esc=1.0
   endif
do 13 n=1,5
   sin(ie,m,n,le)=esc.abs(sflux(ie+1,m)*cs(ie+1,m,n,le))
   * sflux(ie,m)*cs(ie,m,n,le))/2.
   * 1.e-27*(evs(ie+1)-evs(ie))*xn1r(n)
   ple(le)=ple(le)+sin(ie,m,n,le)
13       continue
12       continue
11       continue

For E > 1000 MeV, with constant cross sections

ptle(1e)=0.0

rewind(20)
do 14 it=1,45

read (20,*), evt(it), fluxt(it)

if (evt(it) .ge. 1.e9) then
  do 15 m=1,5
    if (m .le. 2) esc=1.0
    if (m .ge. 3) then
      if (evt(it) .gt. (ion*lam)) esc=0.0
      if (evt(it) .le. (ion*lam)) esc=1.0
    endif
  do 16 n=1,5
    tflux(it,m)=xf1(m)*fluxt(it)
    tin(it,m,n,le)=esc*tflux(it+1,m)+tflux(it,m))
  *     /2. * cs(19,m,n,le) * 1.e-27*
  *     (evt(it+1)-evt(it)) * xnrr(n)
  ptle(1e)=ptle(1e)+tin(it,m,n,le)
16       continue
15       continue
endif
14       continue

Production of light elements multiplied by the
lifetime of AGN (10^8 years)
tagn=pi*1.e15

xle(1e)=(ple(1e)+ptle(1e))*tagn

10 continue

C Decay time of 10Be

 t10be=pi*3.9e13

C Decay time of 7Be

 t7be=4.7e6

xle(2)=xle(2)+xle(4)

xle(4)=xle(4)*exp(-tagn/t7be)

xle(6)=xle(6)*exp(-tagn/t10be)

xle(7)=xle(7)+xle(6)*(exp(tagn/t10be)-1.)

xlib=(xle(1)+xle(2)+xle(3))/(xle(5)+xle(7)+xle(8))

xbbe=(xle(7)+xle(8))/xle(5)

write (nout,99994) '6Li/H = ', xle(1)

write (nout,99994) '7Li/H = ', xle(2)

write (nout,99994) '9Li/H = ', xle(3)

write (nout,99994) '9Be/H = ', xle(5)

write (nout,99994) '10B/H = ', xle(7)

write (nout,99994) '11B/H = ', xle(8)

write (nout,99994) 'Li/(Be+B)= ', xlib

write (nout,99994) 'B/Be= ', xbbe

99999 format (1x,e9.2)
99997 format (1x,e9.2,e12.3,e12.3)
99996 format (1x,a,i4)
99995 format (1x,e10.2,e14.3)
99994 format (1x,a,e10.3)
99993 format (1x,e10.2,e14.3,e14.3)
   end

function fst(en)
 implicit double precision (a-h,o-z)
 double precision lam,ion
 dimension r2(46),ev(46)
 integer kount
 common /telnum/kount
 common /lower/ilimit
 common /lamda/lam,alpha,ion
 i=ilimit
 kount=kount+1
 c     Energy Range (g cm^-2)
 r1=en/ion
 r2(i)=ev(i)/ion
 c     Function
 fst=en**(-alpha)*exp(-(r1-r2(i))/lam)
 return
 end
B.3 Boron Ionization Structure

The next FORTRAN program solves the set of equations (Eq. 4.6, together with Eqs. 4.7-4.12) that describes the ionization balance for boron. The input file defines the value of the ionization parameter in the region of interest, so this value can be varied in the calculation. Then, it computes the relative strength of the BIII (λ2066 Å) emission line with respect to the Hβ recombination line, by using Eqs. 4.25-4.27 and the parameters defined in Section 4.3. This result also changes with variation of the ionization parameter.

c23456**********Boron Ionization Structure***************
c
This program calculates the ionization structure of Boron in a Narrow Line Region gas of an AGN, by equating photoionizations to recombinations.
Auger transitions are included when there is a K-shell ionization.

implicit double precision (a-h,o-z)
double precision phief(5),phi(5,2),rec(5),a(5,2),b(5,2),
et(5,2),phr(6),xb(5),ac(2),fre(2),em(2),
& xe(2),q(2)
c Constants (eV, s)
h=4.136e-15
pi=3.141569
c Compute K-shell and L-shell ionization rates
c Define Parameters (eV, cm, s)
dens=1.e4
ah=6.3e-18
ahel=7.9e-18
ahet=1.6e-18
rcloud=1.e14

open (7, file='borinput', status='old')
write (6,*) 'Flux'
read (7,*) Flux
write (6,*) Flux

open (1, file='phics.d', status='old')
do 1 i=1,5
  read (1,*) et(i,1), et(i,2), a(i,1), a(i,2), b(i,1), b(i,2)
do 2 j=1,2
  fh=exp(-1.e-2*dens*ah*rcloud)
  fhe1=exp(-1.e-2*0.05*dens*ahel*rcloud)
  fhe2=exp(-1.e-2*0.05*dens*ahe2*rcloud)
  if (et(i,j).ge.54.4) then
    phi(i,j)=4*pi*flux*a(i,j)/h*fh**((13.6/et(i,j))**3)
    & fhe1**((24.6/et(i,j))**3)*fhe2**((54.4/et(i,j))**3)*(11.8/(-1.5-b(i,j))
    & *(2000**(-1.5-b(i,j))-et(i,j)**(-1.5-b(i,j)))+0.0256/
    & -0.7-b(i,j))*(5000**(-0.7-b(i,j)))-2000**(-0.7-
    & b(i,j)))))
  elseif (et(i,j).ge.24.4) then
    phi(i,j)=4*pi*flux*a(i,j)/h*fh**((13.6/et(i,j))**3)
    & fhe1**((24.6/et(i,j))**3)*(11.8/(-1.5-b(i,j))**
    & (54.4**(-1.5-b(i,j))-et(i,j)**(-1.5-b(i,j)))+fhe2*)
elseif (et(i,j) .ge. 13.6) then
  phi(i,j) = 4*pi*flux*a(i,j)/h*fh**((13.6/et(i,j))**3)
  * (11.8/(-1.5-b(i,j))*(24.6*(-1.5-b(i,j))-et(i,j))**
  (-1.5-b(i,j))*fhei*(54.4*(-1.5-b(i,j))-24.4*(-1.5
  -b(i,j)))+fhe2*(2000*(-1.5-b(i,j))-54.4*(-1.5
  -b(i,j)))+0.0256*fhei*fhe2/(-0.7-b(i,j))*(5000*(-
  0.7-b(i,j))-2000*(-0.7-b(i,j))))
elseif (et(i,j) .ge. 8) then
  phi(i,j) = 4*pi*flux*a(i,j)/h*(11.8/(-1.5-b(i,j))*(
  13.6*(-1.5-b(i,j))-et(i,j)**(-1.5-b(i,j)))*(24.6**
  (-1.5-b(i,j)))-13.6*(-1.5-b(i,j)))*fh+fhei*(54.4**
  (-1.5-b(i,j)))-24.6*(-1.5-b(i,j)))+fhe2*(2000*(-1.5
  -b(i,j))-54.4*(-1.5-b(i,j)))+0.0256*fh*fhei*fhe2/(-
  0.7-b(i,j))*(5000*(-0.7-b(i,j))-2000*(-0.7-b(i,j))))
endif

2 continue
1 continue

c Compute effective ionization rates (including Auger
Transitions)

c Recombination Coefficients
c rec(1)=8.2e-13
rec(1)=1.e-12

c rec(2)=4.8e-12
rec(2)=8.e-12
rec(3)=7.e-12
rec(4)=1.e-11
rec(5)=1.98e-11

phief(1)=phi(1,1)+phi(1,2)
do 3 l=2,3
   phief(l)=phi(l,1)+phi(l,2)+dens*rec(l-1)*phi(l-1,1)/
   &  phief(l-1)
3 continue
do 4 k=4,5
   phief(k)=phi(k,1)
4 continue

Compute Ionization Fractions for Boron
phr(1)=1.0
pht=1.0
do 5 i=1,5
   phr(i+1)=phief(i)/(dens*rec(i))*phr(i)
   pht=phr(i+1)+pht
5 continue
xb0=1.0/pht
do 6 i=1,5
   xb(i)=xb0*phr(i+1)
6 continue

Compute excited state populations for BII and BIII
Collisional strengths and A coefficients
q(1)=4.8e-10
q(2)=2.7e-10
ac(1)=1.3e9
ac(2)=1.9e8
fre(1)=2.2e15
fre(2)=1.45e15
do 7 m=1,2
  xe(m)=dens*q(m)/ac(m)

  c    Compute relative emission wrt Hbeta
  em(m)=h*fre(m)*xe(m)*ac(m)*xb(m)/(1.24e-25*dens
    +   *6.2415e11)
  7 continue

  c    Write Results

  write (6,99999) 'B0/B(total) = ', xb0
  write (6,99999) 'B+/B(total) = ', xb(1)
  write (6,99999) 'B2+/B(total) = ', xb(2)
  write (6,99999) 'B3+/B(total) = ', xb(3)
  write (6,99999) 'B4+/B(total) = ', xb(4)
  write (6,99999) 'B5+/B(total) = ', xb(5)
  write (6,99999) 'j(B2+)/j(Hbeta) = ', em(2)

99999 format (1x,a,e10.3)
end
Appendix C

Spallation Reaction Data

We present here several tables and plots of the spallation cross sections as a function of energy corresponding to the collisions between a proton and a C, N and O nucleus, and to the collisions between an α particle and a C, N and O nucleus. In addition, we present the table and plot of the nuclear cross sections for the collision of a He nucleus with another He nucleus. All these collisions lead to new, light isotopes.

The most recent and complete set of spallation data is given by Read and Viola (1984). However, the fits to the spallation cross sections in this paper correspond to the formation of elements with different atomic number A, without distinguishing between the actual isotopes (i.e., Li, Be or B) that are formed. We used these same fits and multiplied them by the fraction corresponding to the formation of Li, Be and B. We derived these fractions from some experimental data, presented in the same paper, which provided information about what kind of isotope was formed.

The data listed in Tables C.1-C.7 are read in the FORTRAN program shown in Appendix B.2, which computes the spallation products in an AGN narrow line region. These data points are plotted in Figures C.1-C.7 in order to show the particular behavior of the spallation cross sections as a function of energy; they show a peak at typical energies from 20 to 50 MeV, and then remain constant for the rest of energies for which the data exist (up to about 5000 MeV). The nuclear cross sections show practically the same behavior, but the peaks are much sharper. The cross sections are given in mb ($10^{-27}$ cm$^2$) and the energy of the moving nucleus in MeV.
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**Table C.1** Cross sections for the spallation reaction $p + ^{12}\text{C}$. 
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Table C.7  Cross sections for the spallation reaction $^4\text{He} + ^{16}\text{O}$. 
Figure C.1 Cross sections for the spallation reaction $p + ^{12}C$. 
Figure C.2 Cross sections for the spallation reaction $p + ^{14}\text{N}$. 
Figure C.3  Cross sections for the spallation reaction $p + ^{16}O$. 
Figure C.4 Cross sections for the nuclear reaction $^4\text{He} + ^4\text{He}$. 
Figure C.5  Cross sections for the spallation reaction $^4\text{He} + ^{12}\text{C}$. 
Figure C.6  Cross sections for the spallation reaction $^4\text{He} + ^{14}\text{N}$. 
Figure C.7 Cross sections for the spallation reaction $^4\text{He} + ^{16}\text{O}$. 