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High Velocity Flows, Shocks in the Star Forming H II Region: the Orion Nebula

by

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Doctor of Philosophy

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Abstract

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We have studied the high velocity flows and related shock phenomena in the Orion Nebula. Hubble Space Telescope WF/PC and WFPC2 images have been used in morphological studies and proper motion studies of the objects of interest. The high spectral resolution échelle slit spectra have been obtained for the central Orion Nebula in order to study both high velocity flows associated with compact objects and large scale high velocity systems.

A group of Herbig-Haro objects located to the north of the Trapezium cluster have been studied in detail. Their morphology, proper motions and motions along the line of sight have been investigated. A bow shock model has been applied to predict the emission line profiles of bow shocks and the resultant line profiles were compared with the observed spectra. The comparison was successful except there is a discrepancy for one of the objects. The possible origin and evolution of this group of objects have been discussed. Two Herbig-Haro objects(HH203/HH204) in the vicinity of θ²A have
also been studied both through the HST images and slit spectra. The possible nature of HH203 was suggested by comparing the emission line image with bow shock model predicted emission in inhomogeneous density environment. The spectra of Knot C has been presented and the nature of this object was discussed. We also reported the discovery of a Herbig-Haro like object–HH269, which is located to the southwest of the Trapezium cluster.

A slit spectra mapping of the vicinity of the Trapezium cluster and HH202 have been done. The high velocity flows associated with several “proplyds” have been studied. A 1’ diameter “receding disk” near the Trapezium cluster was found in [O III] line spectra. A couple of complicated extended high velocity systems were found near HH202. The spectra of this region were presented.
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Chapter 1

Introduction

It is well known that physics is an experimental science. A physicist does measurements in a laboratory before he/she derives results and makes contributions to our knowledge on nature. As a branch of physics, astrophysics has prepared the largest laboratory for astrophysicist — the universe. This chapter intends to give a general description about our specific laboratory in astrophysics: H II Regions, and what other workers have done in this field of our interest. Goals of this study are also presented.

1.1 H II Regions and the Orion Nebula

1.1.1 Physics of H II Regions

Static Picture

H II regions or diffuse nebulae are observed as extended emission line sources in our own Galaxy as well as in other nearby spiral or irregular galaxies. Since some of the objects in this class are so bright and extended in the sky, H II regions have always come to people’s attention soon after a new observational technique had become available. As a famous galactic H II region, the Orion Nebula has been discovered as early as 1611 (Ashbrook 1984) by Nicholas Peirsesc in France. People started
spectroscopic study on H II regions in the 19th century and they were unable to identify some of the emission lines (for example: \(\lambda 5007\text{Å} \) and \(\lambda 4959\text{Å} \)). So the nature of H II regions remained a mystery until the development of quantum mechanics and the work by Strömgren(1939). Bowen(1928), using the knowledge of quantum physics, was able to identify those emission lines as collisionally excited “forbidden” lines from doubly ionized oxygen, which could only be observed in a low-density environment. Strömgren proposed that H II regions are actually interstellar gas ionized by ultraviolet radiation from hot stars, which set the foundation of research in this field. Ever since then, extensive works on the physical properties of H II regions have been done and our knowledge on the subject has improved a great deal. Works done by Osterbrock(1989) and Spitzer(1978) would cover most of the detailed physics involved in H II regions that we understand up to date.

H II regions are usually ionized by a Population I star or star cluster of O- or early B-type, since these are the most luminous in the ultraviolet radiation. Inside H II regions, the photoionization process is balanced by the recombination of ions and electrons. Since both processes happen everywhere in the ionized volume, photoionization-recombination equilibrium is usually achieved. Only photons with \(\hbar \nu > 13.6\text{eV} \) are capable of ionizing hydrogen atoms from the ground state, so the equilibrium equation for an H II region in a homogeneous infinite pure hydrogen medium should be:

\[
N_{H^0} \int_{\nu_0}^{\infty} \frac{4\pi J_\nu}{\hbar \nu} a_\nu d\nu = N_e N_p \alpha_A
\]  

(1.1)
where \( J_\nu \) is the mean intensity of radiation (in energy units per unit area per unit time per unit solid angle per unit frequency interval) at the point (including contribution both from ionizing star and diffuse radiation). \( 4\pi J_\nu / h\nu \) is the number of incident photons per unit area per unit time per unit frequency interval, and \( a_\nu \) is the ionization cross section for H by photons with \( \nu > \nu_0 \). The left hand side then represents the number of photoionizations per unit volume per unit time. \( N_{H^0}, N_p \) and \( N_e \) are the neutral atom, proton and electron densities, and \( \alpha_A \) is the recombination coefficient; so the right hand side gives the number of recombinations per unit volume per unit time.

As a good first approximation for optically thick H II regions, On-The-Spot (OTS) approximation assumes that an ionizing photon from diffuse radiation (recombination to the ground state) is absorbed by another hydrogen atom locally. So the ionization caused by stellar radiation is balanced by recombinations to excited levels only. Under OTS approximation, in equation (1.1) \( J_\nu \) now represents stellar radiation only and can be expressed in term of stellar luminosity per unit frequency interval \( L_\nu \).

\[
4\pi J_\nu = \frac{L_\nu}{4\pi r^2} e^{-\tau_\nu} \tag{1.2}
\]

where \( r \) is the distance to the ionizing source and optical depth

\[
\tau_\nu = \int_0^r N_{H^0} a_\nu \, dr \tag{1.3}
\]

So equation (1.1) now can be rewritten as:

\[
\frac{1}{4\pi} \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} \frac{N_{H^0}}{r^2} e^{-\tau_\nu} a_\nu \, d\nu = N_e N_p \alpha_B \tag{1.4}
\]
Here $\alpha_B$ is the recombination coefficient for recombinations to energy levels $n \geq 2$ of the hydrogen atom. Now if we integrate both sides of the equation over radius of the H II region

$$\int_{\nu_0}^{\infty} \frac{L_{\nu}}{h\nu} d\nu = Q_{H^0} = \frac{4\pi}{3} r_s^3 N_H^2 \alpha_B$$

(1.5)

$Q_{H^0}$ represents the total number of ionizing photons emitted by the star which is balanced by the total number of recombinations to excited levels within the ionized volume, which is usually called the Strömgren sphere, and $r_s$ is the radius of this ionized sphere.

In a static H II region, thermal equilibrium is achieved and the kinetic temperature of the region is fixed. The heating process is caused by photoionization. When an ionizing photon is absorbed by an H II region, a free electron with an initial energy $h(\nu - \nu_0)$ is produced and rapidly thermalized. From previous discussion about photoionization equilibrium we know that the number of recombinations must balance the photoionization process. Thus the difference between the initial and thermalized energies of the electron is the net energy gain for the H II region. On the other hand, an H II region loses its energy through radiation. Free-free emission is one of the energy loss mechanisms for H II regions. While the major energy loss happens when an electron collisionally excites an ion to a higher level which emits a photon that escapes the nebula later. In the cooling process, the most abundant elements H and He contribute much less than the ions like $O^+, O^{++}$, and $N^+$. As we know, the excited energy levels of H and He all have potential higher than 10eV which is much
higher than the kinetic energy $kT$ of free electrons, while ions mentioned above have energy levels only a few electron volts above the ground level, which makes them the far more important coolants in spite of their lower abundance. Equation (1.6) gives a summary of thermal equilibrium in H II regions.

$$G - L_R = L_{FF} + L_e$$

(1.6)

where the left hand side is the "effective heating rate", energy gain from photoionization($G$) subtracted by the energy loss by recombination($L_R$). The right hand side gives the two energy loss terms, free-free emission($L_{FF}$) and collisional excitation($L_e$).

The emitted spectrum of H II regions allows us to analyze radiative processes and determine physical conditions like density, temperature, composition and kinematics of the objects where the radiation comes from. In addition to continuum radiation, bright emission lines are characteristic features in H II region spectrum. Emission lines originate from two different radiative processes, recombination and collisional excitation. The recombination-line spectrum of H II regions are emitted from downward radiative transitions following the capture of electrons to excited levels by the ion at higher ionization stage. In the optical range, most well-known emission lines from H I, He I and He II are recombination lines. Radio recombination lines can be used in H II region's temperature and density measurements. Collisional excitation lines are produced by downward "forbidden" transitions following the collisional excitation of atoms or ions by electrons. These "forbidden" transitions are truly forbidden in terrestrial environment because before these low probability transitions can happen,
collisional de-excitation by electrons will have taken place. Therefore people were not familiar with these emission lines when they were first observed in H II region spectra. Now it is understood that in the nebular environment with orders of magnitude lower electron density, these transitions are no longer collisionally quenched and emission lines of this kind do offer us a great deal of help in understanding the physics of H II regions. For example, in the optical region of the spectrum, [O III]λ4363 and [O III]λ5007,4959 or [N II]λ 5755 and [N II]λ6583,6548 can be used to measure the temperature of H II regions. As shown in Figure 1.1a, both ions have energy-level structure such that emission lines come from two different upper levels with considerably different excitation energy. And the relative rates of excitation to $^1S$ and $^1D$ levels depend very strongly on temperature, so the relative strength of lines emitted from these levels can be used to do electron temperature measurement. Another example is the measurement of electron density using [O II] or [S II] lines. Figure 1.1b shows that these ions give rise to a pair of emission lines from upper levels with nearly the same excitation energy. So the relative excitation rates at the two upper levels depend only on the ratio of collision strengths. As a result, if the two levels have different radiative transition probabilities or different collisional de-excitation rates, the relative populations of the two levels will depend on the density, so does the ratio of intensities of the lines they emit. Continuum radiation in the optical range is rather weak. Dust-reflected starlight, atomic free-bound transitions and two photon decay of the $2^2S$ level of H are components of the optical continuum. In the infrared
region, the continuum is mainly thermal re-radiation of UV energy absorbed by dust particles and emission from free-free transitions. The free-free continuum dominates the rather strong radio-frequency continuum. The properties of dust particles in the H II regions can be studied through continuum radiation.

Dynamic Picture

Looking at features in an H II region or even better, studying the H II region spectroscopically, one can see that H II regions are far from static. Dynamic processes happen everywhere in a H II region due to the nature of its formation and evolution as well as other interactions between gas and their interior contents or their surroundings. Internal random motions (turbulence) in the order of 10 km s\(^{-1}\) are also taken as an explanation for the extra spectral line width besides thermal broadening in H II regions. The physics involved in shock front and ionization front are basic to understanding many of these dynamic processes.

Let's consider a pulse of increased pressure propagating through a gas. Since the sound velocity in the compressed region is higher than in the surroundings, the front of the pulse tends to steepen until a nearly discontinuous shock front is formed. This kind of shock front appear whenever supersonic motion is present. We expect to see shock fronts as a common phenomena in H II regions where the cloud velocities and velocities of other flows are often much greater than the sound speed. In non-magnetized H II regions, we can relate physical quantities on each side of the front
Figure 1.1  Energy-level diagram of the $2p^2$ ground configuration of [O III], and [N II], $2p^3$ ground configuration of [O II], and $3p^6$ ground configuration of [S II] (after Osterbrock 1989).
from equations of conservation of mass, momentum and energy:

\[ \rho_1 v_1 = \rho_2 v_2 \]
\[ p_0 + \rho_0 v_0^2 = p_1 + \rho_1 v_1^2 \]
\[ v_0^2 + \frac{2\gamma}{\gamma - 1} \frac{p_0}{\rho_0} = v_1^2 + \frac{2\gamma}{\gamma - 1} \frac{p_1}{\rho_1} \]

where \( \rho, v, p, \gamma \) are mass density, gas velocity, gas pressure and ratio of specific heat.

Subscript 0 and 1 denote physical parameters ahead and behind the shock respectively.

It is always convenient to use reference frame moving with the shock front. From these three conservation laws, it is easy to derive the “jump condition”:

\[ \frac{p_1}{p_0} = \frac{2\gamma}{\gamma + 1} M^2 - \frac{\gamma - 1}{\gamma + 1} \]
\[ \frac{v_1}{v_0} = \frac{\rho_0}{\rho_1} = \frac{\gamma - 1}{\gamma + 1} + \frac{2}{\gamma + 1} \frac{1}{M^2} \]

where “Mach number” \( M \) of the shock is defined by:

\[ M^2 = \frac{\rho v^2}{\gamma p} = \frac{v^2}{C^2} \]

And \( C \) is the sound speed. It is worth noticing that equation (1.9) for energy conservation is no longer valid when the shock is radiative. As shown on Figure 1.2, the radiative shock front should include a transition region where particles are cooled down through radiation and compressed until equilibrium is established. The radiative shock model has been well accepted in explaining the Herbig-Haro objects which we will discuss in next section.

In addition to the shock front, the physics of an ionization front can also be described. The dimension of the transition zone between the ionized and neutral gas
Figure 1.2  Schematic diagram of radiating shock. (after Spitzer 1978)

is characterized by the mean free path of an ionizing photon:

$$\lambda_{mfp} = \frac{1}{N_H \rho a_\nu}$$  \hspace{1cm} (1.13)

Where $\lambda \sim 10^{-3} \text{pc}$ for a density of $N_H = 10^3 \text{cm}^{-3}$. Therefore it is a good approximation that ionization front is actually a discontinuity of physical parameters like $\rho$, $v$, $p$ and degree of ionization. Across this front, conservation of mass and momentum still holds while the rate of flow of gas through the ionization front is fixed by the flux of ionizing photons arriving at the front, since each ionizing photon produces one electron-ion pair. Conservation of energy should be rewritten as:

$$v_0^2 + \frac{2\gamma}{\gamma - 1} \rho_0 + q^2 = v_1^2 + \frac{2\gamma}{\gamma - 1} \rho_1$$  \hspace{1cm} (1.14)

where $q^2$ is the kinetic energy per unit mass transferred to the gas in the ionization process.
The classic model for the formation and evolution of H II regions is that it starts forming after a hot star was instantaneously "turned on" in an infinite homogeneous neutral hydrogen cloud. At the beginning, very close to the star, the ionizing photon flux is large and an ionization front moves into the neutral gas supersonically, leaving the ionized gas behind it slightly compressed and moving outward with subsonic velocity. The ionization front at this stage is referred to as an R-type front. As the R-type front runs out into the gas, the ionizing flux decreases both because of geometrical dilution and because of recombinations and subsequent absorption of ionizing photons behind the front. When the radius of the ionized region approaches the size of the Strömgren sphere, the speed of the ionization front reduces so that the expansion of the ionized material, caused by the pressure imbalance between ionized material and neutral material, become important as it now can catch up with the ionization front. Once the disturbance in the ionized region catches up with the ionization front, a shock front is formed and it breaks off from the ionization front and propagates to the neutral region. Now the ionization front is referred to as a D-type front. The shock front compresses the neutral material as it passes by which slows down the ionization front further. Theoretically this process will proceed until the pressure is balanced, however the main sequence life time of an O star is shorter than the time this process requires. The H II region actually keeps evolving during its life time. To look back at equation (1.5), if we consider the expansion of the ionized region, the assumption we used for (1.5) $N_e=N_p=N_H$ is thus not valid. So the
modified form should be:

$$Q = \frac{4\pi}{3} r^3 N_p N_e \alpha_B + 4\pi r^2 V_{if} N_{H^0}'$$

(1.15)

where $V_{if}$ is the speed of ionization front and $N_{H^0}'$ is the number density of hydrogen atom in the region between the ionization front and the shock front.

The spherical symmetric expansion model of H II regions has its limit in application to many optically observed objects. Many H II regions have been revealed by radio-frequency measurements of molecular emission lines that they are located in or near the edges of dense molecular cloud and the ionization fronts are propagating into the cloud. Apparently the exciting stars of these objects have formed near the edges of the clouds. It is a selection effect that many optically observable H II regions are located in or close to the near side of molecular clouds, since other H II regions buried deep in the clouds or near the far side of the clouds must be invisible because of the large optical depth of the clouds. After studying the velocity fields of these H II regions plus some detailed work on objects like NGC1976, the Orion Nebula, people proposed the "champagne" or "blister" model for these type of objects (Zuckerman 1973). It is easy to imagine that if an ionizing star turns on close to the edge of the molecular cloud, say at a distance $d < r_\lambda$ (the strömgren radius in the cloud), the ionization front will propagate spherically symmetrically until $r$ reaches $d$. The R-type ionization front will then break out into the less condensed medium (which usually has particle number density $\sim 1 \text{ cm}^{-3}$, 2–3 orders of magnitude less than that in the molecular cloud) and runs out more rapidly due to the large pressure imbalance
caused by the density discontinuity. A rarefaction wave will form at the cloud boundary and move through the ionized region inward causing an outflow of the ionized material. Many model calculations have been carried out (Tenorio-Tagle et al. 1979, Bodenheimer et al. 1979). Figure 1.3 shows the velocity field derived from a two dimensional numerical simulation of the champagne model. It has been a success for the champagne or "blister" model in explaining many observed properties, such as the velocity field in NGC1976. However the complicated "turbulent" type of velocity field is still not explained. People tend to believe that the turbulent motion is caused by the small-scale density structure of the molecular cloud that the ionization front is running into (Osterbrock 1989). Considerable effort has been put into this subject and among them, Von Hoerner (1951), Roy & Joncas (1985), O'Dell (1986) have tried to characterize the turbulence in H II regions.

In general, research in H II regions has made considerable progress in the past few decades and is getting more and more attention in astrophysics. The subject offers us the most accessible probe of interstellar abundances which leads us to a better understanding of the chemical evolution of our own Galaxy as well as distant galaxies. H II regions also provide an excellent site for the study of star formation and related phenomena optically since otherwise the star forming processes will be invisible to us due to the great optical depth of the molecular clouds in which the processes are going on. Further more, the physics of H II regions can be extrapolated
Figure 1.3  Cross section of dense molecular cloud (in lower part of figure) ionized by star (at triangle), expanding into low-density inter-cloud medium (in upper part of figure). (after Osterbrock 1989)
to other subjects such as planetary nebulae, supernova remnants and active galactic nuclei.

1.1.2 A General Description of the Orion Nebula

As a nearby anti-galactic center H II region, the Orion Nebula (NGC1976 or M42) has been extensively studied ever since its discovery. Not only because of its proximity and relatively uncluttered direction, but also the high surface brightness made the Orion Nebula the most studied object of its class in early years. In modern days, the Orion Nebula attracted people's attention as an very active star forming region and the enormous data base that has been built for the Orion Nebula makes it also a good site to explore new problems and to test new theories. As a matter of fact, the Orion Nebula has been studied from one end of the electromagnetic spectrum to the other. New observing techniques, such as the unprecedented high spatial resolution imaging achieved by the Hubble Space Telescope, have always been applied to it quickly. Numerous modeling attempts have been done either on the Nebula itself or using the Nebula as a primary test. All of the above give us the chance to use the Orion Nebula as our site investigating the star formation related phenomena.

The Orion Nebula is located at the middle of the Sword of the Constellation Orion. As revealed on the CO map (Figure 1.4), the Constellation Orion is full of H II region- molecular cloud complexes. We find that the Orion Nebula lies on the near side of the Orion A Cloud. More specifically, the Nebula is associated
with a dense clump of the Cloud named Orion Molecular Cloud (OMC-1) with a molecular hydrogen density $\sim 10^5$ cm$^{-3}$ (Goudis 1982). The brightest part of the Orion Nebula extends approximately one fifth of a degree on the sky and its location is at $\alpha(2000)=5^h35^m$ and $\delta(2000)=-5^o23'$. The Nebula is estimated to be 440 pc away from us (Warren et al. 1977). In the central region of the Orion Nebula, the electron temperature $T_e$ is in the range from 7000 K to 10000 K, and the electron density $N_e$ is about $10^3$ to $10^4$ cm$^{-3}$ and gradually decreases to $\sim 10^2$ cm$^{-3}$ far away from the center (Goudis 1982). The age of the Orion Nebula is still open to discussion. Estimates are of the order of $10^5$—$10^6$ years (Herbig & Terndrup 1986).

Figure 1.5 shows a broad band H$\alpha$+[N II] image and a schematic drawing of the Orion Nebula. The four central ionizing stars denoted as $\theta^1$ Ori A, B, C and D compose the so-called Trapezium group and they are believed to be the major ionizing sources of the Nebula with $\theta^1$ C as the dominant one. Two other ionizing stars lie about 3'$^\prime$ southeast of the Trapezium and they are named $\theta^2$ Ori A and B with A being more prominent. All of the six stars are early O or B type stars and the main ionizing source $\theta^1$ C is an O6 star with an apparent visual magnitude of 5.12 (Lee 1968 & Carruthers 1969). The most prominent large scale optical features include the bright bar-like structure lying 2'$^\prime$ southeast of the Trapezium. It is believed to be the ionization front viewed edge on because emission from high ionization ions like [O III] is much stronger to the side of the bar containing the ionizing source the Trapezium. The obscure feature to the east of the Trapezium is called the dark-bay which is believed
Figure 1.4 CO map of the Orion constellation. (after Henbest and Marten 1983)
to be foreground neutral material from the OMC-1 that wraps around the nebula. The brightest nebulosities lie about 40'' to the southwest of the Trapezium where the [S II] density peaks in the density map. According to numerous kinematic studies of the Nebula in the optical and radio regions, the ionized material is accelerated away from the ionization front (Kaler 1967). And the ionized gas has an average heliocentric radial velocity at about 17 km s\(^{-1}\). The molecular line studies show that OMC-1 is moving away from us at a velocity of 26 km s\(^{-1}\). The foreground neutral "lid" has a velocity of 22 km s\(^{-1}\) as indicated by H I 21 cm absorption line study (van der Werf & Goss 1989). A series of detailed spectroscopic studies with high spatial and spectral resolution carried out by Castañeda (1988), Jones (1992) and O’Dell & Wen (1992) have led to a better understanding of the ionization structure (along the line of sight) of the Orion Nebula, which is summarized in Figure 1.6. In order to explain the observed properties of the Nebula such as the morphology and kinematics, geometric models have been proposed based on the basic champagne phase model. Figure 1.7 shows the qualitative model proposed by O’Dell & Wen (1992) indicating that the ionized material would be redirected by the neutral lid. The first quantitative geometric model based on the density, surface brightness and thickness map of the Nebula was proposed by Wen (1993). Figure 1.8 shows one of the resultant ionization fronts which is successful in explaining observed features such as the bright bar.

In addition to the large scale features, more and more fine scale features in the Orion Nebula have come to people’s attention along with the improvement of ob-
Figure 1.5 Upper half: Broad band Hα+[N II] photograph of M42 and M43 (after Malin 1979). Lower half: Schematic representation of the most important optical features of the Orion Nebula (M42, M43) (after Balick et al. 1974).
Figure 1.6  The three-dimensional ionization structure model for the M42 region (after O'Dell et al. 1993a).
Figure 1.7  The qualitative ionization structure model of M42 (after O'Dell & Wen 1992).
Figure 1.8  The quantitative geometric model of central M42 region by Wen (1993). The height of $\theta^0 C$ is set to 0. The six line segments standing vertically on the ionization front denote the positions of the $\theta^1$ and $\theta^2$ stars. The horizontal line at height 0 indicates the projected position of the bright bar.
serving techniques. Stellar size compact sources, bright optical knots and other filamentary structures with sizes range from arcminutes to the observational limit are revealed in the Nebula. Spectroscopic and proper motion studies show that many of these features are associated with highly supersonic spatial velocities. The morphology, kinematics, physical properties and possible nature of these objects are going to be discussed in this work.

1.2 Herbig-Haro Object: Observation and Modeling

Herbig-Haro objects are shocks occurring in supersonic flows from very young stars. These objects have been recognized as important phenomena in star forming regions for a long time, however it was not until recently that we can relate Herbig-Haro objects to the global star formation process physically through observations and modeling. This section only intends to give a brief summary of the historical development of this rapidly growing subject as well as our current understanding of these objects as a class. Detailed reviews on this subject can be found in works by Reipurth(1991), Böhm(1990), or Dyson(1987).

1.2.1 Observations

Herbig(1948,1950,1951,1952) and Haro(1952,1953) discovered a number of tiny, semi-stellar nebulae in their surveys of dark clouds. These objects display characteristic emission line spectra of hydrogen and forbidden low excitation lines mainly of [O I],
[N II] and [S II] with very weak continua. Ambartsumian (1954) subsequently coined the name Herbig-Haro objects (hereafter HH objects) for this class of tiny nebulae. From their location in dark clouds where nebulous stars or T Tauri stars usually appear, it was concluded in early years that HH objects are somehow related to the star formation process. Herbig and Haro found about 40 objects that are listed in the catalogue of Herbig (1974). Subsequently more and more HH objects have been found because of the increasingly common use of large-field CCD detectors with interference filters. As a result, the designation of names to newly found objects needs coordination. In this work we adopt the naming scheme from Reipurth (1994) where he lists more than 250 HH objects known.

On photographic plates, HH objects appear as groups of small semi-stellar fuzzy nebulae (Herbig 1974). Detailed studies using modern CCD detectors revealed the fine structure of HH objects that consist of bright knots, bows, wisps and streamers of luminous gas. However, attempts to find HH objects purely based on their morphologies on photographic plates or CCD images have not been successful, since the size and general shape of HH objects vary a lot from one to another. Figure 1.9 gives example images of two HH objects in the central Orion Nebula, where one can hardly tell the similarities of morphology of the two objects. On the other hand, the images of HH objects enable us to study their proper motions and usually the resultant tangential velocities of these objects are in the order of a hundred kilometers per second (Jones & Walker 1985).
Figure 1.9  Color composite images of HH201 (upper) and HH203 (lower).
Spectroscopic study of HH objects is a more powerful tool in understanding their physics. The appropriate interpretation of spectra can lead us to physical parameters of HH objects such as density and temperature, and an explanation of their distinct properties such as the nature of low excitation and the characteristic supersonic kinematics. HH objects have been studied in different wavelengths from the ultraviolet to the radio band. In the most studied optical region, it is concluded by early researchers (Böhm 1956, Osterbrock 1958, Haro and Minkowski 1960, Böhm et al. 1973) that for an HH object, permitted and forbidden emission from neutral atoms (e.g. [O I], O I, [C I], [N I]) and from ions of low excitation energy (e.g. Ca II, [Ca II], [Fe II], Mg II, [S II]) are much stronger than in common photo-ionized nebulae, although the line-ratios vary from one HH object to another. Table 1.1 gives lines ratios of HH1 and HH7 which represent "higher" excitation and "lower" excitation HH objects respectively. Most HH objects have line-ratios that lie within the values in table 1.1. Figure 1.10 shows low resolution spectra for several HH objects. On high spectral resolution spectra of HH objects (example shown on Figure 1.11), the striking feature is the considerable radial velocities of the order of a hundred kilometers per second (Schwartz & Dopita 1980). It is also found that 75% of HH objects exhibit negative radial velocities rather than positive velocities due to the fact that the molecular cloud associated with HH objects tends to obscure the objects moving away from us (Cantó 1981).
Table 1.1

Line-ratios of HH objects

<table>
<thead>
<tr>
<th></th>
<th>HH1&lt;sup&gt;a&lt;/sup&gt;</th>
<th>HH7&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>[SII]6717/Hα</td>
<td>~ 0.2</td>
<td>~ 2.8</td>
</tr>
<tr>
<td>[OIII]5007/Hα</td>
<td>~ 0.6</td>
<td>~ 0.1</td>
</tr>
<tr>
<td>[NI]5198/5200/Hβ</td>
<td>~ 0.2</td>
<td>~ 1.8</td>
</tr>
<tr>
<td>[CI]8448/Hδ</td>
<td>~ 0.02</td>
<td>~ 1.3</td>
</tr>
</tbody>
</table>

<sup>a</sup> Brugel et al. 1981, Solf et al. 1988

<sup>b</sup> Böhm et al. 1980, 1983

At near-infrared wavelengths, emission lines of molecular hydrogen are important diagnostics for the molecular component of the HH objects. Shocks or the absorption of ultraviolet radiation can excite vibrational and rotational transitions of molecular hydrogen. The 2.12 μm ν=1-0 the S(1) line of H₂ is the strongest and the most commonly studied line. Many HH objects have been searched for H₂ emission (Brown et al. 1983, Simon & Joyce 1983, Zealey et al. 1984 1986, Lane & Bally 1986, Lightfoot & Glencross 1986, Sandell et al. 1987, Schwartz et al. 1987, Zealey et al. 1989, Allen & Burton 1993) and many were detected and mapped with single-beam techniques. It is found on high resolution infrared spectra that the width of S(1) line is typically only half of the width of the Hα line and the maximum velocities of H₂ lines are also lower. Comparison of optical and infrared images of HH object associated regions is possible at similar resolution through the use of infrared.
Figure 1.10  Low resolution optical spectra of four Herbig-Haro objects (after Reipurth 1991).
Figure 1.11 High resolution [O I]λ6300 line spectrum of HH201. Vertical axis is relative brightness only.
array detectors. Studies have been carried out by Schwartz et al. (1988), Hartigan et al. (1989), Garden et al. (1990), Wilking et al. (1990), Lane (1989), Hu (1993a). It appears that H$_2$ emission, which traces low velocity shocks around 10 to 40 km s$^{-1}$, occurs mainly in the wings of bow shocks, where the shocks are oblique and thus much weaker (Reipurth 1991). In the ultraviolet spectral region, interpretations of observations are heavily dependent upon reddening corrections (Böhm-Vitense et al. 1982). All the brightest HH objects have been observed in the UV band (Brown et al. 1981, Böhm et al. 1981, 1984, Brugel et al. 1985, Schwartz et al. 1985, Carmeron & Liseau 1990). Emission lines of CIV 1548/1551 and C III 1907/1090 dominate “high-excitation” HH objects’ UV spectra, while fluorescent lines of the Lyman bands of the H$_2$ molecule dominate “low-excitation” objects’ UV spectra. The UV continuum rises towards shorter wavelengths, particularly rapidly between 1700Å and 1620Å with a peak around 1575Å. This is believed to be due to a collisionally enhanced two photon decay mechanism in neutral atomic hydrogen (Brugel et al. 1982), and also fluorescent H$_2$ appears to play a role at the shortest wavelengths (Böhm et al. 1987). Although the study of HH objects at radio wavelength has not been fully developed yet, it definitely plays an important role in obtaining information on the optically invisible part of HH objects and their driving sources that are deeply embedded in the molecular clouds. The HH systems detected in radio region usually contain a central energy source with two lobes extending in opposite directions, suggesting a bipolar confined jet. HH1/2 (Pravdo et al. 1985), HH80/81 (Rodríguez & Reipurth 1989), and HH objects
associated with Cepheus A (Hartigan & Lada 1985, Lenzen 1988) are among those that have been studied at radio wavelengths. It is noted that the radio emission from HH objects are non-thermal (Rodríguez et al. 1989). Cruzius-Wätzel (1990) has shown that bow shocks of bullets or jets moving with super-Alfvénic velocity can accelerate particles that are responsible for the non-thermal radio radiation.

1.2.2 Models

The Herbig-Haro objects have always been related to the formation processes of young stars ever since their discovery, knowing the fact that HH objects are always found close to T-Tauri stars in dark clouds. But the view of how the two phenomena are related to each other had been changing in past several decades. Herbig (1969, 1973) has proposed in a straightforward way that a HH object could be the star-forming nebula itself, but this model didn’t last long because no infrared source has been detected inside HH knots (Mendoza 1969). The first infrared star associated with an HH object was discovered near HH100 by Strom et al. (1974a). Since the source is displaced from the HH object, Strom et al. (1974b) argued that HH knots are small reflection nebulae. However, Schmidt and Miller (1979) showed that the HH emission line knots are unpolarized and thus formed in situ.

Being aware of the strong stellar wind from young stars, Osterbrock (1958) first suggested that the line emission from HH objects are due to the energetic outflows from young stars. The similarity of HH emission and emission from supernova rem-
nants led Schwartz (1975) to propose that HH objects are actually radiative shocks resulting from the interaction of a supersonic stellar wind with the ambient material. Later on they developed their model as the shocked cloudlet model (Schwartz 1978), where the bow shocks are formed when a stellar wind from an embedded young star impinges upon small cloudlets. This model is no longer popular primarily because the infrared studies show that most HH objects are facing away from their driving sources which contradict the shocked cloudlet model. Also the observed large proper motion of HH objects tend to be another difficulty for this model because it is hard for a wind-accelerated cloudlet to remain stable (Różyczka & Tenorio-Tagle 1985).

The interstellar bullet model was proposed by Norman & Silk (1979). They consider that Rayleigh-Taylor spikes form when the circumstellar shell breaks up due to instabilities, and a supersonic stellar wind then sweeps them up. These spikes should provide the sites of H₂O masers since they are extremely dense and confined by ram pressure. Later on, these dense clumps of gases are accelerated by the stellar wind and ejected into the ambient cloud, which are observed as HH objects. The interstellar bullet model works well in explaining large proper motion or the direction of the motion. Still the stability of these dense clumps being accelerated by stellar wind remains a problem.

Cantó (1980) and Cantó & Rodríguez (1980b) suggested a wind cavity model for HH objects. They consider the geometry of an isotropic stellar wind when the driving source is located at the edge of a dense cloud. If there is a pressure gradient developing
into the cloud, there will be a ovoid-shaped cavity formed around the wind source. When the wind first hit the oblique walls of cavity, it is refracted towards it’s tip, where the flow converges and shocks against itself. This shock is identified as an HH object. This model indicates the HH shock is stationary so that it is incompatible with the observed large proper motion of most HH objects.

The currently well accepted model for HH objects’ origin and their association with infant stars is the collimated jet model. Through detailed studies on objects like HH34 (Reipurth et al. 1986, Bührke et al. 1988), HH46/47 (Dopita et al. 1982, Meaburn & Dyson 1987, Hartigan et al. 1990) and HH111 (Reipurth 1989, Rodríguez & Reipurth 1994), it has been realized that a large fraction of the known HH objects are likely to be radiative shocks formed when highly collimated supersonic bipolar outflows (jets) from young stars interact with the ambient materials. Much detailed modeling work have been done within this scenario. The origin and collimation of jets have been modeled both with a hydrodynamic approach (Cantó 1983) and a Magnetohydrodynamic (MHD) approach (Pudritz 1988). The comparison of these models with observations is hard to carry out since small scales and high extinction are involved in observations. Models for jet structure have been constructed in the form of steady, non-adiabatic jets (Falle et al. 1987, Cantó et al. 1989, Raga et al. 1990, 1991). More realistic models with velocity and direction variabilities have also been investigated (Raga 1995). The most up-to-date models give a new possible clump acceleration scheme (the break-up of continuous outflow) to the “interstellar
bullet" model, which makes the bullet model applicable to those HH objects that
don't show jet-like flows. At the head of the jets, numerous shock models have been
constructed (Raga 1994). A relatively straightforward bow shock model has been
proposed by Hartigan et al. (1987), in which the emission from a radiative bow shock
from a set of 43 planar shock models is calculated and they predict the spectral line
profile, line ratios, the spatial velocity and orientation of the shock. More details
about this model and its application of it will be discussed in section 3.1.3.

It is obvious that the modeling of HH objects is still an on-going process. The
comparison of models with observations is a very important step in understanding
the true nature of HH objects and ultimately the processes of star formation.

1.3 Purpose of This Study

As mentioned before, the observation of star formation is very limited due to the fine
scales and high extinction involved. In other words, the manifestation or phenomena
closely related to the star forming processes are the key information sources we have.
In general, we intend to collect and analyze scientific data on high velocity flows in
the central Orion Nebula, which are believed to be associated with the ongoing star
formation process.
1.3.1 Study of the Herbig-Haro Objects

This thesis reports on original investigations of the Orion Nebula region with both unprecedented images and unique spectroscopic studies. The post-refurbishment Hubble Space Telescope has made observations on the central Orion Nebula with Wide Field and Planetary Camera 2. The images made available to us have reached an unprecedented high resolution of 0\".0991 pixel\(^{-1}\) for the Wide Field camera and 0\".046 pixel\(^{-1}\) for the Planetary Camera. We make use of these high resolution images to study the morphologies of HH objects. Proper motions of HH objects have also been determined by comparing positions on HST images taken four years apart. This proper motion study gives us information both on the direction of motion and on the tangential velocities of these objects. We also use the Coudé Feed system combined with an échelle grating spectrograph at Kitt Peak Observatory to obtain high spectral resolution slit spectra of all the known HH objects in the Orion Nebula. The radial velocities of these objects are revealed in these spectra. As a result, a full picture of the motion of these HH objects is established.

As discussed in previous sections, various shock models have been proposed for the HH objects. We chose the bow shock model proposed by Hartigan et al.(1987) to fit our spectral line profiles of some of the HH objects. In the process of exploring the model input parameter space, we are able to give a possible physical solution for these objects, such as the ionization status of the preshock material and the most
likely model is either the "bullet" or "shocked cloudlet". The possible origin and time scale of these HH objects are also discussed.

1.3.2 Other Compact Sources and Large Scale High Velocity Systems

The central Orion Nebula region is full of compact sources besides HH objects. Tens of them have been identified as ProtoPlanetaryDisks(Proplyds)(O'Dell et al. 1993b). Spectroscopic studies on some of these objects in the vicinity of the Trapezium have been carried out. Combined with the high resolution HST images, the spectroscopic study help us investigate the high velocity flows associated with these objects.

Large scale high velocity flow systems were found close to the Trapezium cluster and HH202. We did a spectroscopic long slit grid mapping survey of this region. The reduced data are presented and possible explanations are discussed.
Chapter 2

Data Acquisition and Reduction

In this study, Hubble Space Telescope WF/PC high spatial resolution images are used to study the morphologies and proper motions of the high velocity features. Long-slit spectra of emission lines of high spectral resolution are used in studying the kinematic properties of the features. This chapter intends to summarize the observation and data reduction.

2.1 Hubble Space Telescope Imagery

2.1.1 The Instrument

The Hubble Space Telescope (HST) is a 2.4m aperture F/24 Ritchey-Chrétien telescope (Hall 1982, Burrows et.al 1991). Wide Field and Planetary Camera 2 (WFPC2) is one of the five scientific instruments on board. The scientific objectives of the WFPC2 are to provide photometrically and geometrically accurate, multi-band images of astronomical objects over a relatively wide field-of-view, with high angular resolution across a broad range of wavelengths. The three Wide-Field Cameras (WFC) at F/12.9 provide an “L” shaped field of view of 2.5×2.5 arcminutes with each 15μm detector pixel subtending 0.10 arcseconds on the sky. In the Planetary Camera (PC) at F/28.3, the field-of-view is 35×35 arcseconds, and each pixel subtends 0.046 arc-
seconds. Each of the four CCD's covers 800×800 pixels and is sensitive from 1200Å to 11000Å. The optical configuration of WFPC2 is shown on Figure 2.1.

A few images used in this study were taken in the Wide Field Camera mode of the original Wide Field and Planetary Camera (WF/PC). WF/PC was launched aboard the HST in April 1990 and was designed to operate from 1150Å to 11000Å with a resolution of 0.1 arcseconds per pixel (Wide Field Camera, F/12.9) or 0.043 arcseconds per pixel (Planetary Camera, F/30), each camera mode using an array of four 800×800 CCD detectors (MacKenty et al. 1992). WF/PC was replaced by WFPC2 during the first Maintenance and Refurbishment Mission in December 1993.

2.1.2 The Observation and Data Reduction

The main HST data source of this study is from the work by O'Dell & Wong (1996). This group of observations were made from December 1993 to March 1995 using the post-refurbishment WFPC2. For the proper motion study, a few images taken by WF/PC were also used and those observations were made in August to September 1990 and August 1991. Hereafter, we name the two group of data as "new data" and "old data" respectively.

New Data

The new data are a combination of three observing programs, Guaranteed Time Observer program GTO-5085 with C.R.O'Dell of the Rice University as principal
Figure 2.1 The optical configuration of the Wide Field and Planetary Camera 2 of the Hubble Space Telescope.

investigator, General Observer program GO-5469 with J.Bally of the University of Colorado as the principal investigator and an Early Release Observations (ERO) program whose purpose was to illustrate the successful installation of WFPC2.

The field-of-view for the observations were chosen so that a continuous coverage of the central portion of the Orion Nebula was possible. The various field-of-views are shown in Figure 2.2. Four filters were employed so that the strongest emission can be recorded and a reasonable range of ionization conditions can be represented. The F658N filter is dominated by the 6584Å emission line of [N II], which arises from a low ionization thin layer near the hydrogen ionization front. The F656N filter primarily records the H I recombination line at 6563Å which arises from the largest emission zone of the nebula. The F502N filter presents the [O III] 5007Å emission which comes
from the highest ionization region within the nebula. The F547M (medium band centered at 547nm) isolates a region free of strong nebular emission, thus allowing easy detection of stars and correction of the narrow bandpass emission line filters for continuum radiation. The exposure time was selected according to the local surface brightness to avoid overexpose of the high surface brightness central region of the nebula. The exposure times and dates of observations are listed in Table 2.1.

Table 2.1

<table>
<thead>
<tr>
<th>Exposure Time(s)</th>
<th>F502N</th>
<th>F656N</th>
<th>F658N</th>
<th>F547M</th>
<th>Observation Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERO</td>
<td>400</td>
<td>350</td>
<td>600</td>
<td>100</td>
<td>Dec 29, 1993 &amp; Jan 8, 1994</td>
</tr>
<tr>
<td>GTO</td>
<td>200</td>
<td>200</td>
<td>500</td>
<td>50</td>
<td>Nov 1994–Feb 1995</td>
</tr>
<tr>
<td>GO</td>
<td>180</td>
<td>60</td>
<td>180</td>
<td>30</td>
<td>Mar 21–Mar 22 1995</td>
</tr>
</tbody>
</table>

The reduction of ERO images has been described by O'Dell & Wen (1994). These reduction processes are different from those performed on other images because of very early date of these WFPC2 observation. All other images have gone through the routine "pipeline" processing at the Space Telescope Science Institute (STScI) as preliminary reduction. In addition, cosmic ray elimination, bad pixel editing, mosaicing of the images and smoothing of the seams at the junctures of the CCD frames have
Figure 2.2  Field of views of HST observations overlaid on the chart from Strand's (1958a, 1958b) catalogue. (After O'Dell & Wong 1996)
been done on the images. The determination of an astrometric solution for each field is the key process for our proper motion studies. During the process of mosaicing the four CCD frames together, the geometric distortion effect which stems from optical and mechanical design constraints (wide field of view and small optical bench volume) and off-axis optics has been corrected (Gilmozzi et al. 1995). The Orion stars catalogued in Jones & Walker (1988) were used to obtain plate solutions. As has been discussed several times previously (Prosser et al. 1994, O'Dell et al. 1994, McCaughrean et al. 1994), a zero point correction of +0°.059 to the right ascension has been applied to the Jones & Walker star coordinates. The IRAF* (Image Reduction and Analysis Facility) task "pltsol" was used to fit the (x,y) pixel coordinates to world coordinates (RA, DEC). This fitting routine is based on the Singular Value Decomposition (SVD) method (Press et al. 1989), and is modified to handle double precision. The resultant position accuracy for compact sources is within one pixel (Wong 1995). In O'Dell & Wong's work, a grand mosaic image of the central region of the Orion Nebula has been made. It is worth mentioning that the data used in this study are all from a single field so that full resolution and the highest possible astrometric accuracy is achieved.

*IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc, under cooperative agreement with the National Science Foundation.
Old Data

Two sets of HST data taken with WF/PC were used. One of them pointed to the north of the Trapezium and the other one pointed to the immediate south of the Trapezium, as revealed in Figure 2.3. The observations are summarized in Table 2.2. For field A, the data reduction has been discussed by Hester et al. (1991). Basically very few reduction processes have been performed for this set of data at the time. For field B, the data has been flat-field corrected and cosmic-ray cleaned. Deconvolution using the Lucy program (Lucy 1990) with the reference images produced by the Tiny Tim program was performed on the data in order to enhance the spherical aberration impaired images. The surface brightness of three narrow band filters images, Hα, [O III] and [N II], were also calibrated to absolute energy units (Hu 1993b). As discussed in section 3.1.2, the geometric distortion correction has to be considered for these old data before we can use them to study the proper motions of our objects.

Table 2.2

Old HST Observations

<table>
<thead>
<tr>
<th>Exposure Time(s)</th>
<th>F502N</th>
<th>F656N</th>
<th>F658N</th>
<th>F555M</th>
<th>Observation Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field A</td>
<td>200</td>
<td>600</td>
<td></td>
<td></td>
<td>Aug 26 &amp; Sep 9, 1990</td>
</tr>
<tr>
<td>Field B</td>
<td>300</td>
<td>200</td>
<td>600</td>
<td>10</td>
<td>Aug 13-14, 1991</td>
</tr>
</tbody>
</table>
Figure 2.3 Fields of view of 1990(A) and 1991(B) HST observations overlaid on Strand's (1958) star chart.
2.2 Long-Slit Emission Line Spectra

Detailed kinematic study of compact sources and large scale high velocity systems is one of the major goals of this work. High spectral resolution and large spatial coverage as well as high angular resolution are desired for this purpose. The Coudé Feed long-slit échelle spectrograph at the Kitt Peak National Observatory (Willmarth 1993) was thus chosen for this study. The data we used are from two observing runs carried out in December 1993 and 1994.

2.2.1 Instruments

The optical train of the overall Coudé Feed system is shown on Figure 2.4. A description of each major element of the system is given in this section, proceeding through the light path.

Telescope

It is convenient to set up heavy spectroscopic equipment at a Coudé focus (Walker 1987). The Coudé telescope used in this system is an auxiliary telescope adjacent to the 2.1 m equatorial mount telescope at Kitt Peak. The incoming light is first reflected by the 1.5 m alt-azimuth mount flat mirror (No.1) onto a fixed 0.9 m off-axis parabolic imaging mirror (No.2) which focuses and redirects the light. No.3 is an 0.15 m flat mirror that reflects the light into the entrance slit. Most operations of the telescope are performed with the help of a computer control system.
Figure 2.4 Optical train of the Coudé Feed system.
Image Rotator

The Coudé focus has the property that the field rotates as the telescope tracks a star (Walker 1987). An image rotator was employed to compensate for this rotation. However, the original design of the image rotator was for the 2.1 m telescope rather than the one we are using. Because the field rotation rate of an alt-azimuth mount (1.5m) telescope is different from the constant rate of an equatorial mount telescope (2.1m), frequent manual operation of the image rotator is required in order to keep the projection of the slit on the sky stationary during an exposure. Calculations show that the image rotator needs to be set every three to five minutes at the value:

\[ \text{OBS} = \text{PA} + \beta - \theta - 154^\circ \]  
(2.1)

where PA is the desired position angle of the slit on the sky measured from North counterclockwise, and

\[ \beta = \sin^{-1}\left(\frac{\sin a \sin A^*}{1 + \cos a \cos A^*}\right) \]  
(2.2)

\[ \theta = \sin^{-1}\left(\frac{\cos \phi^* \sin h}{\cos a}\right) \]  
(2.3)

\[ A^* = A + 4^\circ \]  
(2.4)

\[ \phi^* = \phi + 7.5^\circ \]  
(2.5)

where \( \phi = 31.958^\circ \) is the latitude of the Observatory, \( h \) is the hour angle with West being positive, \( a \) is the altitude of the object from:
\[ a = \sin^{-1}(\sin \delta \sin \phi^* + \cos \delta \cos \varphi \cos \phi^*) \] (2.6)

and \( A \) is the azimuth of the object from:

\[ \sin A = \frac{\cos \delta \sin h}{\cos a} \] (2.7)

\[ \cos A = \frac{-\sin \delta \cos \phi^* + \cos \delta \cos h \sin \phi^*}{\cos a} \] (2.8)

For each observing run, calculation of a set of OBS values was part of the preparation beforehand.

**Light Dispersing Elements**

In order to achieve the high spectral resolution (up to a few km s\(^{-1}\)) desired for our study, the échelle grating (Walker 1987) was chosen to be the light dispersing element. The spectral resolution can be derived from the grating equation:

\[ m\lambda = d(\sin i + \sin \theta) \] (2.9)

where \( m \) is the grating order, \( \lambda \) is the wavelength, \( d \) is groove spacing, \( i \) and \( \theta \) are the incident angle and angle of diffraction measured from the grating normal. Usually the linear resolution of the grating on the detector is the measure of spectral resolution:

\[ K \equiv \frac{d\lambda}{dx} = \frac{d\lambda}{d\theta f_{\text{cam}}} = \frac{d\cos \theta}{mf_{\text{cam}}} \] (2.10)

where \( dx \) is the linear size of the resolution element of the detector, \( d\lambda \) is the wavelength interval and \( f_{\text{cam}} \) is the focal length of the camera. The échelle grating achieves
nearly an order of magnitude higher spectral resolution than ordinary grating by using high orders and large diffraction angles. "échelle" means "steps" which is appropriate in describing this class of grating that consists of a series of steps with large blaze angles, other than the low blaze angles of ordinary grating. The échelle grating used in this study has a ruling of 31.6 line mm\(^{-1}\) in an area of 203 × 381 mm\(^2\) with a blaze angle of 63°26' (\(\tan^{-1} 2\)). It was operated at an incident angle of 71° and a diffraction angle of 56°. The grating set-up is also controlled through a computer system.

Since the échelle spectrograph used high orders, the short spectral range led to the problem of contamination of the spectra by light from nearby orders. As a result, order-sorting element had to be used. Traditionally, narrow band interference filters are used to isolate the desired order. For our study, in order to achieve a better spatial coverage, it would be difficult to obtain multiple emission lines for each slit position setting due to the limited observing time. Cross-dispersion using a grism was the better choice for us. The grism separates different orders of the échelle grating spectra in a direction perpendicular to that of the échelle grating dispersion. This method allowed multiple orders of spectra being taken at the same time. We were able to obtain as many as five to seven important nebula emission lines with one grating-grism setting. However, the CCD detector had a finite size which means we could not get as many orders as we wanted. Especially when the long slit was used, if we separated orders completely on the detector, it was impossible to get multiple lines of interest. We had to compromise at this point to make the orders overlap(}
shown on Fig 2.5). This didn't prevent us from getting multiple lines since the nebula emission lines are narrow enough and the chance for two nebula lines from adjacent orders overlapping with each other was very small. The overlap does make a flat field correction unrealizable. See the data reduction section for more discussion.

The grism employed in our two observing runs were Number 650($\lambda = 4950\text{Å}$ for $m=1$) and Number 770($\lambda = 5970\text{Å}$ for $m=1$).

**Detector**

A charge coupled device (CCD) was used as detector in this system. A CCD is an array of photon-sensitive semiconductor capacitors. During an exposure, electrons are generated within each element due to the photoelectric effect. These electrons are accumulated in the capacitors until the end of the exposure. At the end of an exposure the charge packets in each row are transferred along the columns successively to the subsequent rows. The charges in the final row are delivered individually to on-chip amplifier where they are converted to output voltages. These voltages are then digitized and stored in a computer (Walker 1987). CCD's are now the most popular detector used in astronomy. Compared with other detectors such as photographic plates or phototubes, CCD's have much larger dynamic range, higher quantum efficiency, broader spectral response and higher linearity. Furthermore, CCD data are in digital format and thus make it easier to use a computer to store, reduce and analyze data.
Figure 2.5  Sample whole CCD image of cross-dispersed échelle spectra. The horizontal axis is along wavelength dispersion. Cross-dispersion by the grism occurs along the vertical axis.
The CCD's used in our observing runs were T1KA(1024×1024 24μ pixels) and F3KD(3072×1024 15μ pixels) respectively.

In addition to these major elements, the collimator employed in the system was an f/31.2 off-axis parabolic mirror with a focal length of \( f_{\text{col}} = 686 \) cm. The camera (No.5) was a folded Schmidt design with a focal length of \( f_{\text{cam}} = 108 \) cm. The plate scale at the slit was \( 7''.23 \text{ mm}^{-1} \), so the plate scale at the CCD is \( 7.23 \times f_{\text{col}}/f_{\text{cam}} = 45''.92 \text{ mm}^{-1} \). Along the slit direction, a pixel of linear size \( p \) will be projected on the sky with an angular size of \( 45''.92p \text{ mm}^{-1} \), and perpendicular to the slit, the projection would be \( 45.92p \times \cos \theta/\cos i = 78''.87p \). Thus for the first run, the scale at the T1KA CCD was 1''.10 pixel\(^{-1} \) perpendicular to the dispersion and 1''.89 pixel\(^{-1} \) parallel to the dispersion. The slit width used was 450 \( \mu \), which corresponds to a velocity resolution of 3.6 km s\(^{-1} \). For the second run, the scale at the F3KD CCD was 1''.38 pixel\(^{-1} \) (double-binned) perpendicular to the dispersion and 1''.18 pixel\(^{-1} \) parallel to the dispersion. The slit width used was 490 \( \mu \), which corresponds to a velocity resolution of 3.9 km s\(^{-1} \). The slit width was set to the above values so that the resolution of the spectrograph was maximized without losing the efficiency of the system. The slit length used for nebular observation was always the longest available(25.68 mm), corresponding to decker No. 1. and its projection on the sky is \( \sim 3' \).

Finally, it is important to note that for an extended source, the speed of a spectrograph is independent of the telescope aperture size. For our nebula observation, the Coudé Feed spectrograph system is the best available choice we had.
2.2.2 Observation Procedures

Each night before the observation, preparation work had to be done in order to save critical observing time. Usually we started with uncovering the optics of the telescope and turning on the computer control system. The grating had to be set using the grating control program, filters had to be put in to cut off certain wavelength range of light as needed. The CCD was tested at this stage. It was first examined for possible bad pixels by taking flat field exposures. Then several narrow slit exposures were taken using the Thorium-Argon lamp to check the alignment of the CCD chip with respect to the slit. This step was very important to make sure the dispersion direction was along a line of pixels so that the wavelength calibration can be accurate. The focus of the camera was adjusted next based on the line profiles of a series of comparison lamp spectra. The focus with narrowest and symmetric lines was considered the best. After the focus was adjusted, the slit was set to the observing value and calibration spectra were taken. Calibration spectra include bias exposures which were used to correct the across-chip variation of the read-out noise. Flat-field exposures were not taken for our observation due to reasons discussed in the previous section. Comparison spectra were taken at this stage too which were used to estimate where nebular emission lines were going to fall on the CCD. Slight adjustment of the grating was possibly necessary to avoid nebular lines from different orders overlapping each other or to obtain extra nebula lines without sacrificing lines in our primary observing plan.
When the Orion Nebula was high enough in the sky, we first fed the coordinates of the Trapezium stars into the computer system to command the telescope locating the object. The guider box was used to bring the prominent stars onto the TV screen and the telescope’s focus was adjusted using the guider at this time. The image rotator was adjusted to the appropriate value to obtain the desired slit orientation on the sky. For some of the exposures, a guiding star on the slit was used. We made marks on the TV screen and used the guider box to do fine guidance keeping the position of the star as stable as possible. The orientation of the slit was controlled by adjusting the image rotator every 3 to 5 minutes which gave a PA accuracy of the slit better than \( \pm 2^\circ \). Due to our choice of cross-dispersion discussed in last section, the continuum spectra of the guiding star could be a problem when the orders overlap with each other (see Figure 2.6). Hence for most of the exposures taken during the 1995 observation, we offset the slit from the guiding star to a known distance. The slit position accuracy was not as good as using a guiding star on the slit, but it helped us getting as much information as possible from the spectra. During the night, a couple of extra Thorium-Argon comparison spectra were taken in between the observations in order to make wavelength calibration as accurate as possible.

2.2.3 Data Reduction

The first observing run was carried out from December 28, 1993 to January 2, 1994. The second observing run was from December 16, 1994 to December 22, 1994. Figure
Figure 2.6  Sample whole CCD image of cross-dispersed échelle spectra with guiding star on slit.
2.7, 2.8 and 2.9 show the slit positions on the Orion Nebula chosen for the two observing runs. Table 2.3 lists slit positions and orientations, all the observed ions for each position, the integration time and major features that fall in each slit position.

**Table 2.3**

<table>
<thead>
<tr>
<th>Slit</th>
<th>[O I][S II]</th>
<th>[O III]</th>
<th>[S II][Ne][N II]</th>
<th>He I</th>
<th>Position/Orientation(PA)</th>
<th>Major feature</th>
</tr>
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<td>A1</td>
<td>2700</td>
<td>3600</td>
<td></td>
<td>2400</td>
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<td>$\theta^2A/285$</td>
</tr>
<tr>
<td>A2</td>
<td>3600</td>
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<td>1800</td>
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<td>2400</td>
<td>$\theta^2A/233$</td>
</tr>
<tr>
<td>A3</td>
<td>3600</td>
<td>2700</td>
<td>1200</td>
<td>2400</td>
<td>2400</td>
<td>$\theta^2A/191$</td>
</tr>
<tr>
<td>A4</td>
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<td>2700</td>
<td>1200</td>
<td>2400</td>
<td>2400</td>
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<td>A6</td>
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<td>1800</td>
<td>1800</td>
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<td>1800</td>
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<tr>
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<td>2400 x2</td>
<td>1200 x2</td>
<td>1200 x2</td>
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<td>HE203</td>
</tr>
<tr>
<td>B2</td>
<td>2400 x2</td>
<td></td>
<td></td>
<td></td>
<td>$15^\circ N$ of $\theta^2A/BW$</td>
<td>HE203</td>
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</tr>
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<td></td>
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<td>LV5/F20/[O III] hole</td>
</tr>
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<td></td>
<td></td>
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<td>HE202 system/[O III] hole</td>
</tr>
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<td>$\theta^2B/EW$</td>
<td>HE202 system/[O III] hole</td>
</tr>
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</tr>
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<td></td>
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<td>B24</td>
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<td></td>
<td></td>
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<td>HE202 system</td>
</tr>
<tr>
<td>B25</td>
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<td></td>
<td></td>
<td>$5.50^\circ W$ of $\theta^3C/NS$</td>
<td>HE202 system</td>
</tr>
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</table>
Figure 2.7  Slit positions on the sky for the 1994 observing run.
Figure 2.8  Slit positions for 95 observing run. The $[\text{O} \ III] \lambda 5007$ line was obtained at these positions.
Figure 2.9 Additional slit positions for the 95 observing run. Lines from low ionization ions such as [O I], [N II], [S II] etc. and Hα were obtained at these positions.
### Table 2.3 (cont')

<table>
<thead>
<tr>
<th>[O I] + [S III]</th>
<th>[O III]</th>
<th>[S II], [N II]</th>
<th>Position/Orientation</th>
<th>Major Feature</th>
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<td>7.00° W of θ²C/NS</td>
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</tr>
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<td>8.89° W of θ²C/NS</td>
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</tr>
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<td>3.5° W of θ²A/NS</td>
<td>HH203</td>
</tr>
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<td>3038³</td>
<td>11° N of θ²B/EW</td>
<td>HH202</td>
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<tr>
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<td>1800 x4</td>
<td>1800 x4</td>
<td>HH206/EW</td>
<td>HH208</td>
</tr>
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<td>3600</td>
<td>3600</td>
<td>HH201/EW</td>
<td>HH201</td>
</tr>
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<td>3600 x2</td>
<td>HH207/EW</td>
<td>HH207</td>
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<td>3600³ +1800 x2</td>
<td>HH206/EW</td>
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<td>3600 +1800 x2</td>
<td>HH205/EW</td>
<td>HH205</td>
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<td>1800</td>
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<td>3600 +1800 x2</td>
<td>JW595/356</td>
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<td>1800 x4</td>
<td>JW544/330</td>
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<td>1800 x4</td>
<td>JW544/315</td>
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<td>JW544/265</td>
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<td>JW544/262.4</td>
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<td>1800 x2</td>
<td>JW544/231</td>
<td>HH208</td>
</tr>
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</table>

¹Cloudy.
²Seeing was bad.

The reduction of our échelle spectra was performed in several steps. First, bias frames taken for each night were combined together to form one "zero" image. Then the bias subtraction was performed for all the spectra using "zero". This is to subtract a fixed pattern in the "zero" frame, which is the median of all the bias frames.
obtained. Then an "overscan" correction were applied to all the spectra of the night, both comparison spectra and spectra on objects. This step basically subtracts the average signal of the overscanned region which is part of the CCD detector that was not exposed to light during an exposure. Trimming off the unused part of the CCD was done along with the "overscan" correction in order to reduce the size of the spectra. Flat-fielding was not done for our data due to the overlap of orders along the cross-dispersion direction. Cosmic ray removal of the spectra was made easier by the multiple exposures taken during the observing run. Cosmic ray hits were rejected by comparing the two or more nearly identical exposures. In order to identify the orders in comparison spectra, short slits had to be used to avoid overlap of orders. Before the wavelength calibration could be done, one had to identify the corresponding orders in comparison spectra and actual observations. After the desired order of comparison spectra was found, the dispersion solution between the pixel coordinates and wavelength was established. This relationship was transformed to the corresponding object spectra. So the wavelength calibration had to be done order by order. Finally the wavelength was converted to heliocentric velocity. First the observed wavelength $\lambda$ is converted to the geocentric velocity $V_e$ based on the Doppler's Law:

$$V_e = \frac{\lambda - \lambda_0}{\lambda_0}c$$

(2.11)

where $\lambda_0$ is the rest wavelength of a line (Osterbrock et al. 1992), $c$ is the speed of light. Then the heliocentric velocity $V_s$ is obtained via the relation:

$$V_s = V_e + V_{rev} + V_{rot}$$

(2.12)
where $V_{rev}$ and $V_{rot}$ are the velocities of the revolution and rotation of the Earth about the Sun:

$$V_{rev} = 29.974 \cos \beta \sin(\lambda_s - \lambda) + 0.501 \cos \beta \sin(\Gamma - \lambda)$$ \hspace{1cm} (2.13)

$$V_{rot} = 0.465 \sin h \cos \delta \cos \phi = 0.395 \sin h \cos \delta$$ \hspace{1cm} (2.14)

where $\lambda$ and $\beta$ are the ecliptic longitude and latitude of the object, $\lambda_s$ is the longitude of the Sun. $h$ is the hour angle and $\phi$ is the geometric latitude of the observatory and

$$\Gamma = 280^\circ 13'15''.00 + 6189''.03T + 1''.63T^2 + 0''.012T^3$$ \hspace{1cm} (2.15)

is the solar perigee at the epoch of observation. $T$ is in tropical centuries since 1900.0.

All these basic data reduction were carried out using the IRAF packages on our SUN workstation at Rice University. For a detailed description of the steps, one can refer to handbooks such as "A User's Guide to CCD Reductions with IRAF" by Philip Massey(1992) and "A User's Guide to Reducing Slit Spectra with IRAF" by Philip Massey et.al(1992).
Chapter 3

Herbig-Haro Objects in the Orion Nebula

3.1 A Group of Objects to the North of the Trapezium

A group of seven Herbig-Haro Objects located to the north of the Trapezium was discovered in a series of studies by Münch & Taylor(1974), and Axon & Taylor(1984). Currently their designated names are HH201, HH205–HH210 (Reipurth 1994) while they were formerly referred to as M42–HH1, HH5–HH10 before the Reipurth catalog became available. Figure 3.1 shows the positions of these objects relative to the Trapezium and nearby infrared sources. This section will give a thorough discussion of these objects from observation to model simulation.

3.1.1 Data Analysis

Among this group of Herbig-Haro objects, HH201, HH205, HH206, HH207 and HH210 are prominent on low ionization optical emission line images, such as [N II], [O I], etc. [N II] images shown on figure 3.2. reveal their general morphology. It appears that all of the objects are elongated along a specific axis and are approximately in the range of 2”–6” along that axis, which translate to 0.0042 to 0.013 pc at Orion’s distance of 440 pc. The objects usually consist of multiple bright knots. The overall
Figure 3.1  Schematic diagram of the northern Orion region. Positions of Herbig-Haro objects and infrared sources in this region are shown.
bow shape of these objects indicates the presence of bow shocks. On high ionization emission line images such as the [O III] image, these objects are absent.

Figure 3.3 shows high resolution [O I]λ6300 spectra of HH201, HH205 and HH210. All three long-slit spectra show the emission from these objects to occur in a range of velocities. Although HH201 and HH210 show very high blue shifted components (up to 400 km s$^{-1}$), HH205 shows a nearly symmetric velocity flow both blueward and redward. The physics indicated by these peculiar spectral features are discussed in the following sections.

3.1.2 Kinematic Studies

The kinematics of these HH objects have been studied in detail. The proper motions have been determined comparing two sets of HST images taken $\sim$4 years apart. The heliocentric velocities along the line of sight have been determined using the slit spectra.

Proper Motion

The tangential motion of these HH objects in the plane of the sky can be determined from study of their proper motions. Previous work by Jones & Walker(1985) suggested that these objects have proper motions as high as 11$"$/century which translates to $\sim$0.1$"$/year. This result motivated us to use two sets of our HST WF/PC narrow band filter images at 0.1$"$/pixel resolution to study the proper motion of these objects.
Figure 3.2  [N II] images of HH201 (upper left), 205 (upper right), 206 (middle left), 207 (middle right), 210 (lower image). Each small image box has the size of 6.4" × 6.4". The lower image is twice as larger.
Figure 3.3  Images of the spectral line \([\text{O I}]\lambda 6300\) of HH201 (upper), HH205 (middle), HH210 (lower).
HH201, HH205 and HH206 are the prominent objects on the HST images that were found to have large proper motions. The first set of images, referred to as "old data" in a previous chapter, were taken in August to September 1990, before the refurbishment mission. The newer data were taken in November 1994 to February 1995, after the successful refurbishment of HST. The high spatial resolution of HST should enable us to detect proper motions of these HH objects if the magnitude of the motions are as high as mentioned above during this period of time.

Since the two sets of data used were taken by WF/PC and WFPC2, the image qualities and reduction procedures for the two sets of data were different. In the process of determining the astrometric solution for both fields of view, slight difference in plate scale up to 2% were found so that one set of images was magnified to match the plate scales. In order to make the position comparison as accurate as possible, for each pair of objects, a field star nearby was used to register the images. By doing so, the error introduced by the astrometric solution was minimized and the only considerable systematic error in our proper motion study comes from the geometric distortion.

Both WF/PC and WFPC2 are subject to geometric distortion which originate from optical and mechanical design constraints (wide field of view and small optical bench volume) and off-axis optics (Gilmozzi et.al. 1995). The distortion ranges from a few tenths of a pixel in the center of each chip, up to 2–3 pixels at the edge of each chip. Unfortunately geometric distortion correction is a standard data reduction
procedure only for WFPC2 data. Our 1990 set of images were not corrected for this effect. An estimate of the error introduced by geometric distortion effect has been obtained using the results from Gilmozzi et al.'s study (1995). A FORTRAN program was employed in calculating the position offset on WF/PC chips at the position of our objects and field stars due to the geometric distortion. Since registered field stars were used in our study, only the relative positions of HH objects with respect to the stars affect our proper motion study results. The estimate shows that the average uncertainty in the "relative" HH object positions is about 7% of the amount of the corresponding proper motion result.

Another uncertainty in the proper motion study comes from the actual measurement of the position of the HH objects. As shown in Figure 3.4–3.6, these HH objects have a linear size of approximately 2″, and for some of them, especially HH205, the morphology changed significantly during the four years time interval. It is a somewhat ambiguous task to choose the corresponding points on two images to do the position measurement. As indicated in Figure 3.4–3.6, we decided to choose the brightest knots on the HH objects as the reference point, except for HH205, where we chose the "middle" point of the whole object in order to diminish the effect from the change of the general shape of this object. The results of the proper motion study are summarized in Table 3.1. 440 pc was used as the distance of the Orion Nebula in converting the proper motion to velocity units. Figure 3.4–3.6 are the actual pairs of contour plots of HST [N II] images of these HH objects that were used to do the
measurements. As a reference, we put Jones & Walker's proper motion results in Table 3.1 too. It appears that our result agrees with Jones & Walker's study fairly well for both HH201 and HH205. The meaning of our proper motion results needs to be discussed combined with other information and section 3.1.4 will thoroughly discuss related matters.

**Table 3.1**

Results of the Proper Motion Study

<table>
<thead>
<tr>
<th></th>
<th>This Study</th>
<th>Jones &amp; Walker (1985)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu_x$</td>
<td>$\mu_y$</td>
</tr>
<tr>
<td></td>
<td>(&quot;/century)</td>
<td>(&quot;/century)</td>
</tr>
<tr>
<td>HH201</td>
<td>4.6</td>
<td>6.9</td>
</tr>
<tr>
<td>HH205</td>
<td>3.5</td>
<td>11.6</td>
</tr>
<tr>
<td>HH206</td>
<td>5.5</td>
<td>10.9</td>
</tr>
<tr>
<td>HH210</td>
<td></td>
<td></td>
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</table>

**Spectroscopic Study**

Spectroscopic study of these HH objects is essential in understanding their kinematics as well as other physical properties. The only previous systematic slit spectroscopy of this group of HH objects was obtained and discussed by Axon & Taylor (1984) in their discovery paper. However the velocity resolution of their instruments were 30 km s$^{-1}$ to 60 km s$^{-1}$. Spectroscopy with higher spectral resolution was certainly desirable
Figure 3.4 Contour plots of HH201 in "old" (upper) and "new" (lower) HST observations, with one field star (at lower right corner) registered. The cross denotes the position we used to measure the proper motion. The plate scale is one tenth of an arcsecond.
Figure 3.5 Contour plots of HH205 in "old" (left) and "new" (right) HST observations, with one field star (at lower left corner) registered. The cross denotes the position we used to measure the proper motion. The plate scale is one tenth of an arcsecond.
Figure 3.6  Contour plots of HH206 in "old" (upper) and "new" (lower) HST observations, with one field star (at lower left corner) registered. The cross denotes the position we used to measure the proper motion. The plate scale is one tenth of an arcsecond.
in order to study the detailed emission line profile and to establish physical models based on them.

We used the Coudé Feed system at Kitt Peak National Observatory to obtain high velocity resolution spectra at a resolution of 3.9 km s\(^{-1}\) on most of the HH objects in this group, namely HH201, HH205, HH206, HH207, HH208 and HH210. All of the spectra at [O I] \(\lambda 6300\) show high velocity features, while we chose three objects, HH201 HH205 and HH210 to do a detailed line profile analysis, as their spectra are the strongest and typical in the group. In order to isolate the emission from HH objects, a background nebula emission subtraction was carefully done for each of the objects. We chose a nearby region on the slit with smooth nebula emission and subtracted it from the object emission line profile. All the line profiles showed in Figure 3.7 were subjected to this subtraction. Examining Figure 3.3 shows that our low spatial resolution of \(\sim 4''\) (due to the combined effect of guiding error and seeing conditions) made the objects unresolved spatially while Figure 3.7 clearly shows that the line profiles of these objects are very well resolved in the velocity dimension. As a reference, a Gaussian profile fit is put on each of the profiles at the nebula emission line in Figure 3.7. One can see that velocity components contribute to the FWHM of the line profiles in addition to thermal broadening since the contribution from turbulence or the instrument should be far smaller than the difference between the actual line profile and the thermal line width. As a reference, the thermal broadening
of [O I] λ6300 line should be:

\[ \sigma = \frac{\lambda}{c} \sqrt{\frac{2kT}{m}} \]  \hspace{1cm} (3.1)

if we take \( T = 10^4 \text{K} \) for the Orion Nebula, then \( \sigma = 0.067 \text{Å} \), FWHM = 2.355\( \sigma = 0.159 \text{Å} = 7.57 \text{ km s}^{-1} \), which is far smaller than the line width observed (indicated on Figure 3.7).

Interpretation of this spectroscopic data required the modeling work discussed in the following section.

3.1.3 The Bow Shock Model

Since all of the HH objects we observed have highly supersonic motions, while their ionization are characteristically low, they are believed to be shock ionized. The morphologies of these objects also suggest the presence of bow shocks. Thus the radiative bow shock model has been chosen to study these objects theoretically. Various radiative shock models have been proposed for HH objects. On the basis of planar shock models, P. Hartigan, J. Raymond and L. Hartmann constructed bow shock models in their work in 1987. These models can be used to predict the line ratios and line profiles expected from integrated emission of HH objects. It is straightforward to compare our low spatial resolution spectroscopic data with their theoretical predictions in the case where the whole HH object falls in the slit and contributes to the emission line profile.

As shown in Figure 3.8, the bow shock model assumes axis symmetry. The bow shock is divided into 200 annuli of constant \( \xi \) to calculate the line emission. The result
Figure 3.7  [O I]λ6300 line profiles of HH201, HH205, HH210, with Gaussian fits.
of a plane-parallel shock of velocity $V_\perp$ weighted by the area of the annulus is used as the emission from the annulus. 43 planar shock models with shock velocity ranging from 20 km s$^{-1}$ to 400 km s$^{-1}$ have been used for different annuli. Integration of the annuli over the entire bow gives the expected emission-line profiles and line ratios of the object. The basic assumptions of the model is that the cooling distance is small compared with the size of the bow shock so that the radiation originates in a narrow shell next to the bow. The plane parallel shock models show a power law fit of the cooling distance as:

$$d_{c3} = 12\left(\frac{V_s}{100\text{km}\text{s}^{-1}}\right)^4\frac{100\text{cm}^{-3}}{\eta}\text{AU}$$

where $d_{c3}$ is the distance between the planar shock and the point where $T=10^3\text{K}$, $\eta$ is the preshock number density of neutrals plus ions, and $V_s$ is the shock velocity. For $\eta \sim 10000 \text{ cm}^{-3}$ in the Orion Nebula, $V_s$ of the order of hundreds of kilometers per second would give a small cooling distance ($d_{c3}$) compared to typical size of the HH objects (1500AU). The postshock $V_\perp$ is calculated taking into account both the jump conditions at the shock interface (the velocity decreases by a factor of 4 for a strong shock) and the effect of cooling (decrease by an additional factor of about 10). $V_\parallel$ is taken to be unchanged during cooling which allows the velocity $V_2$ and deflection angle $\theta$ to be calculated. Effectively, the resultant theoretical line profiles consists of the co-addition of a series of expanding rings of emitting material (Fig 3.8). The final line profile is calculated by smoothing the points with Gaussian whose width arises from thermal motions of the emitting ion plus instrumental broadening.
As one of the important input parameters, the shock velocity has to be estimated before running the modeling code. Under the assumption of small cooling distances, \( V_s \) can be estimated from the full width of an emission line (FWZI). We take the postshock \( V_\perp \) (diminished \( \sim 40 \) times) as zero since it is negligible compared with \( V_s \), so that \( V_2 = V_\parallel \) and \( \theta = (\pi/2) - \xi \). The radial velocity of the emitting gas in the frame of reference of the bow shock in the \( xx \) plane is:

\[
V_r = V_s \sin \xi (\sin \xi \cos \phi \pm \cos \xi \sin \phi)
\]  

(3.3)

Setting partial derivatives to zero would give that the maximum and minimum radial velocities occur when \( \xi = (\pi/2) - (\phi/2) \) and \( \xi = \phi/2 \), so the maximum and minimum
radial velocities from a bow shock with respect to the observer are:

\[ MX = \frac{V_s}{2}(1 + \cos \phi) - V_s \cos \phi \]  
(3.4)

\[ MN = -\frac{V_s}{2}(1 - \cos \phi) - V_s \cos \phi \]  
(3.5)

Thus,

\[ FWZI = MX - MN = V_s \]  
(3.6)

The orientation of the shock can also be easily estimated using equation (3.4) and (3.5):

\[ \phi = \cos^{-1}\left( -\frac{MX + MN}{V_s} \right) \]  
(3.7)

For the three objects we studied, HH201, HH205 and HH210, the estimated shock velocities are 310 km s\(^{-1}\), 120 km s\(^{-1}\) and 400 km s\(^{-1}\) respectively. The orientations are estimated as 25°, 90° and 36° with respect to the line of sight, respectively. As a result, the radial velocities of HH201, HH205 and HH210 are 281 km s\(^{-1}\), 0 km s\(^{-1}\) and 324 km s\(^{-1}\). Combining these quantities with the observed tangential velocity (Table 3.1), the observed kinematics of these HH objects are summarized in Table 3.2.

The estimate of shock velocities are used as input parameter for the modeling code. In order to predict the emission line profiles, the modeling code needs other input parameters as well. Physical parameters such as preshock number density, distance to the objects, size of the objects on the sky are chosen to be the realistic values: \(10^4\) cm\(^{-3}\), 440pc and 2″. Two other parameters, the nature of the bow shock and the bow shock shape, were chosen so that the resultant line profile best fit the
observed data. As for the nature of the bow shock, "bullet" models were chosen over the "shocked stationary cloudlet" model, which indicate the bow shocks form around a dense clump of gas ejected into the ambient cloud, rather than form due to a supersonic stellar wind impinging upon a clump of gas in the flow. The geometry of this group of objects (they are all facing away from the suggested driving sources) would indicate the same preference. Bow shape is another input parameter for the code. The resultant line profiles does not depend heavily on this parameter, as most of the emission comes from the tip of the bow. In order to get the best fit with the observed spectra, bow shape "A"(z=0.42r^2+1.0r^4) as referred to by Hartigan et.al in their 1987 paper was used for HH205. For HH201 and HH210, bow shock shape z=0.05r^2 was used instead.

The modeling code adopted from Hartigan et.al.(1987) was run for each of the three objects using the input parameters given above. Figure 3.9 shows the predicted line profiles of [O I]λ6300 overlaid on the actual observed line profiles. The theoretical line should be in the frame of reference of the driving source of these bow shocks. In the case that these objects are "bullets" from a new born star, the predicted line should be in the frame of these stars. Therefore, we chose the frame of the molecular cloud where the star formation is going on as the reference. Since the Giant Molecular Cloud is moving approximately 26 km s^{-1} away from us, the velocity axis is scaled to heliocentric velocity minus 26 km s^{-1}. The flux of the lines have been normalized.
Figure 3.9  Bow shock model predicted line profiles are fit to the actually observed [O I] line profiles.
Table 3.2
Kinematics of HH objects

<table>
<thead>
<tr>
<th>Object</th>
<th>$V_\perp^a$</th>
<th>$V_r$</th>
<th>$V$</th>
<th>Orientation$^b$</th>
<th>$V$</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH201</td>
<td>170</td>
<td>281</td>
<td>328</td>
<td>31</td>
<td>310</td>
<td>15</td>
</tr>
<tr>
<td>HH205</td>
<td>253</td>
<td>0</td>
<td>253</td>
<td>90</td>
<td>120</td>
<td>90</td>
</tr>
<tr>
<td>HH210</td>
<td>215</td>
<td>324</td>
<td>389</td>
<td>34</td>
<td>400</td>
<td>0</td>
</tr>
</tbody>
</table>

$^a$Units for velocities are km s$^{-1}$.

$^b$The orientation is in degrees with respect to the line of sight.

3.1.4 Conclusion and Discussion

Directly from the proper motion study, the association of these HH objects with the infrared sources in IRC2 region is strongly suggested. Looking at Table 3.1, the direction of proper motion are all pointing away from the IRC2 region as if these objects are originated from the same driving source. In addition, the distance between HH201, HH205, HH206, HH210 and IRC2 are roughly proportional to their tangential velocities. Assuming the tangential velocities of these objects have been constant, the time scale for HH201, HH205, HH206 and HH210 traveling from IRC2 region to their current positions are 705 yrs, 1075 yrs, 944 yrs and 1031 yrs respectively. Although result for HH205 might not be accurate due to the uncertainty in the proper motion measurement we discussed previously, still these nearly constant time scales indicate
that these objects are likely from the same source and they originated about the same time. The bow shock model result on the orientations of shocks confirms this conclusion. According to the bow shock model, the orientation of motion of HH201 is almost along the line of sight, which explain naturally that its projected distance from IRc2 is the shortest. On the other hand, HH205 is moving almost in the plane of the sky according to the model, and its position is indeed farthest from the IRc2 on the sky.

As shown on Figure 3.9, the bow shock model can successfully fit the observed emission line profiles of this group of HH objects. Thus the parameters used to run the simulation code can be a set of physical solutions for these objects. As for the nature of these radiative shocks, the bow shock simulation is in favor of the "interstellar bullet" model. Observations by Allen & Burton (1993) in infrared wavelength on this region also support the bullet model. They argue that the linear features on their images(Fig 3.10) are produced by high-velocity "bullets" of interstellar gas explosively ejected from the IRc2. However the "bullet" model has always been unable to answer the question that how small clouds of dense gas could be accelerated up to high velocities without being disrupted. Recent theoretical work by Stone et al.(1995) may have answered the question especially for this region. They argue that the "bullet" could form in the poorly collimated winds from young stars as a result of hydrodynamic instabilities. The central idea of their argument is that these bullets can form by the fragmentation of the dense shell swept up by poorly collimated stellar
wind, rather than by an explosive event at the source. For a steady outflow from a young star expanding into a uniform ambient medium, the thin shell, formed due to the radiative cooling in the swept-up ambient gas, decelerates. The gas in the outflow feels an effective gravity that is directed outwards so that the shell is stably stratified. But if the mechanical luminosity of the wind $L_w \propto t^m$ and the density in the ambient medium $\rho$ is a decreasing power law in distance $\rho \propto r^{-n}$, then the shell will accelerate on the condition that $n+m>2$ (Weaver et al. 1977, Koo et al. 1992). Acceleration of the shell is Rayleigh-Taylor unstable and leads to fragmentation into knots and filaments ("bullets"). Thus time variability or decreasing density can make the fragmentation happen which would lead to the formation of "bullets". For the objects we are studying, the density gradient can be a major factor that allows the mechanism to work. Our observations show that most of the infrared "fingers" on Figure 3.10 have optical counterparts. This indicates that these HH objects suffer little extinction, which means that they are coming out of the denser molecular cloud. The density gradient on the boundary of the molecular cloud can be as large as $n>2$. As a result, these "bullets" could have been formed solely because of the steep density gradient in this region.

Although our study on this group of HH objects has been successful in explaining their nature in various aspects, many questions remain open at this point. The most obvious question is how to reconcile the disagreement between the tangential velocity derived from the proper motion study with the shock velocity derived from
Figure 3.10 Infrared image of the Orion Nebula (after Allen & Burton, 1993). $J$ band, [Fe II] and molecular hydrogen lines are color coded as blue, green and red in this composite image respectively.
the bow shock model for HH205. The discrepancy could arise from the uncertainty of
the measurement of the proper motion. Alternatively, another possible explanation
could be that the preshock material is moving at a considerable velocity too. But no
evidence has been found for this interpretation. Further work is needed to solve the
problem.

3.2 Objects to the South of the Trapezium

3.2.1 HH203/HH204 and Knot C

θ²A Ori is located about 3' southeast of the Trapezium. In the vicinity of θ²A, there
are three objects which show high velocity flow in their spectra. Two of them have
been identified as Herbig-Haro objects, HH203 and HH204, while the other one was
named as knot C in Taylor & Münch(1978)'s study. Figure 3.11 shows the HST
WFPC2 color-coded image of this region. HH204 appears to be a low ionization
bright knot with bow-shaped wings extending to the northwest and west direction.
HH203 shows an asymmetric or incomplete bow shock morphology with a northern
wing extending up all the way to the Trapezium region, while the southern wing is
absent. Knot C has a quite different appearance than the other two. It is a nearly
circular bright knot with a stellar object located at its center.

Similar to what we did in the study of proper motion for the northern HH objects,
we used two sets of HST WFPC images to determine the proper motion for HH203.
The [N II] images we used were described in section 2.1, the first image(Field B of
Figure 3.11  Color coded WFPC2 image of the \( \theta^2\)A region, with slit positions overlaid. \([\text{N II}]\lambda6583\) is coded as red, \(\text{H}\alpha\) is coded as green, and \([\text{O III}]\lambda5007\) is coded as blue.
"Old Data") was taken in August 1991 and the newer image was taken in January 1994. We registered one of the field stars (avoiding use of $\theta^2 A$ because of saturation) on the two images, and tried to measure the position difference of HH203 on the two. However, no detectable position difference was found after a careful examination of the images. This should establish an upper limit on the proper motion of HH203. Taking the measurement uncertainty as one pixel on the images, the proper motion of HH203 would be less than 4.3" per century which translates to a tangential velocity of 90 km s$^{-1}$ at the distance of the Orion Nebula. The proper motion of HH204 has been studied previously by Cudworth et al.(1977) and the proper motion they determined was $\mu_\alpha = 2.4 \pm 0.7"/\text{cent}$ and $\mu_\delta = 1.7 \pm 0.3"/\text{cent}$, which corresponds to a tangential velocity of $71 \pm 15$ km s$^{-1}$ at position angle of 125° (measured counterclockwise from north). This velocity is well within the upper limit of the tangential velocity of HH203. Unfortunately the proper motion of HH204 and Knot C have not been studied as their position are off the field of our "Old" HST image.

Our long slit high resolution spectroscopy has covered this region too. Figure 3.11 shows the slit positions on the sky while Figure 3.12 and 3.13 show the resultant H$\alpha\lambda$6563 two dimensional spectra. Although the morphologies of HH203 and HH204 suggest that they are likely to be bow shocks, their spectra look quite different from those of the northern HH objects. The high velocity components are blue shifted knots rather than continuum-like feature. It is obvious that the scale size of these two bows are much larger than the northern objects, which means they are spatially
resolved in this spectroscopic study and only part of the emission from the bow enters each of the slit spectra. HH204 appears as a fairly wide high velocity feature on the Hα spectra centered at heliocentric radial velocity of $\sim$20 km s$^{-1}$. The tip of the HH203 bow appears as another wide high velocity feature on the spectra centered at heliocentric radial velocity of $\sim$ -45 km s$^{-1}$. The mapping of slit spectra of this region revealed a striking jet feature along the bow axis of HH203. A high velocity feature with heliocentric velocity comparable to that at the tip of HH203 shows up in every slit position along the geometric axis of the bow of HH203. The most natural explanation for this is that we are looking at the driving jet of HH203 (see Figure 3.12, 3.13). The Hα spectrum of Knot C appears to be a continuous feature with both red-shifted and blue-shifted wings (see Figure 3.13 B3'). The fact that the red-shifted wing is more extended than the blueward wing would indicate that the spatial velocity of the shock (if it exists) is going toward the molecular cloud which makes it difficult to fit it in the Herbig-Haro object picture, as the driving sources of HH objects are likely located inside the molecular cloud where the new stars are being born. Furthermore, the existence of a central stellar object makes Knot C more likely to be a proto-planetary disk rather than an HH object. The high velocity feature could even be the bipolar flows from the proto-stellar object itself. More discussion about proto-planetary disks can be found in the next chapter.

As discussed above, the observation indicates that HH203 is likely to be a jet-driven bow shock. The peculiar asymmetric morphology of HH203 can be explained
Figure 3.12 North-south Hα line spectra of the θ²A region. Vertical axes are angular distances (") relative to the declination of θ²A. Horizontal axes are heliocentric velocities in km s⁻¹.
Figure 3.13  East-west Hα line spectra of the θ²A region. Horizontal axes are angular distances (") to the right ascension of θ²A. Vertical axes are heliocentric velocities in km s⁻¹.
by a 3-D model of emission from lop-sided bow shocks. Henney (1995) calculated steady-state models of asymmetrical bow shocks based on the results of Hartigan et al. (1987). The models assume systematic asymmetries in the ambient medium or the jet of HH objects. Figure 3.14 shows a comparison of observed emission line images with the resultant images from the models. All models have a bow shock velocity of 150 km s\(^{-1}\) and the jets propagate in the plane of the sky, the density gradient or pressure skewness is directed along the vertical axis. The left-hand panels show emission from low excitation lines (\(\text{H}\alpha\lambda6563\) for observation and \([\text{S II}]\lambda6716+6731\) for the model results) and the right-hand panels show high excitation lines (\([\text{O III}]\)). The top pair of images show the HST WFPC2 images of HH203. The center two panels show a model with non-uniform ambient density. The density in the top half of the image is 3.4 times that in the bottom half. The \([\text{S II}]\) (Henney stated that “the appearance of the models in \(\text{H}\alpha\) is very similar to that in \([\text{S II}]\)” emission is strongest from the side with the higher ambient density, whereas the \([\text{O III}]\) emission, due to its strong dependence on the shock velocity, is strongest from the low density side, since the bow shock is more “open” to that side. The bottom two panels show a model with a non-axisymmetric jet pressure. In this model, both the high and low excitation lines are stronger from the side towards which the pressure is skewed. Note that the \([\text{O III}]\) emission is the more asymmetric, unlike in the previous model, because of its greater sensitivity to the shock velocity. The comparison shows clear similarity of the HST low ionization image with the density gradient model result (central panels).
high ionization image of HST is too weak to do a comparison which indicates HH203 may have a lower shock velocity than that used in the model. Given the fact that HH203 located near the ionization front of M42 (bright bar), the ambient material is likely to have a high density gradient. The non-uniform density of ambient material is a reasonable explanation for the cause of the morphology of HH203.

3.2.2 HH269

To the southwest of the Trapezium cluster, there is a elliptical form object centered at $\alpha=5^h 35^m 09^s .16 \delta=-5^\circ 23'44''$(2000), and its dimensions are $41''\times 23''$ with the long axis east-west. This object was first recognized by Feibelman (1976). Cudworth et al. (1977) reported large proper motion of several bright knots of this object. Walter (1993, 1994) later on found that the object was also a region of enhanced density which motivated this study. This elliptical form object will be referred to as HH269, using the serial designation of Reipurth (1994) for HH objects since from this study we shall see that this object has many of the properties of an HH object.

The HST WFPC2 imaging of this region (Figure 3.15) shows that HH269 is well defined against the bright background of the nebula in [N II] while it is faintly visible in H\alpha and very weak in [O III]. The low-resolution slit spectra for this study (Walter 1993) covered the range 3700-5050 and 5500-6900Å at a resolution of 7Å FWHM. The slit essentially lay along the long axis of HH269. Electron densities were calculated using the [S II] lines at 6717 and 6731Å without subtraction of the nebular back-
Figure 3.14  Low([N II]) and high([O III]) ionization line images of HH203(upper panels) are compared with model predicted emission line images of bow shocks moving in the the plane of the sky, showing the distinction between asymmetry in the ambient medium(cental panels) and in jet pressure(lower panels). The model predicted lines are [S II](left) and [O III](right).
ground. The sulfur densities arise from a lower-ionization region and have values of 2200, 2500 and 1300 cm\(^{-3}\) in the eastern knot, western knot and central region respectively. Since the ratios are composites of the lower density nebular background (the middle region is characteristic) and the higher density HH objects, these densities are lower limits for HH269. The electron temperature were also examined using the [N II] lines at 5755 and 6583Å. The [N II] temperatures was \(~9000\) K for this region.

High resolution spectra of HH269 were obtained in our 1994 observing run at Kitt Peak National Observatory using the Coudé Feed system. The slit was positioned east-west along the major axis of the object (shown as A9 on Figure 2.7). Line profiles were obtained for H\(\alpha\), [O III]5007Å, [O II]3726 and 3729Å, [S II]6717 and 6731Å, HeI5876Å, and [N II]6548 and 6583Å. The spectra were deconvolved in units of 3 pixels, which extend over 3.3\(\prime\), into multiple velocity components. Previous investigations (Castañeda 1988, O’Dell and Wen 1992, Jones 1992, Wen and O’Dell 1993, O’Dell et al. 1993a) have shown that high-resolution spectra of the Orion Nebula are composed of multiple velocity components which are due to different regions. Therefore, it was not surprising that each line broke down into three velocity systems extending over the 180\(\prime\) length of the slit. These velocity systems naturally grouped themselves according to like velocities with [N II] and [S II] being similar (the low ionization ions) and H I, He I, [O II], and [O III] being similar (the high-ionization ions). The low-ionization systems occurred at 6.5\(\pm\)2.6, 22.4\(\pm\)1.3 and 34.6\(\pm\)2.2 km s\(^{-1}\) with the 22.4 km s\(^{-1}\) being much stronger. The high-ionization systems occurred at
Figure 3.15  Color composite image of HH269. [N II] is coded as red, Hα is coded as green and [O III] is coded as blue.
2.0±0.8, 15.6 ±3.0 and 29.8±1.6 km s⁻¹, with the 15.6 km s⁻¹ being much stronger. All velocities in this section are heliocentric. In this region, these velocity components are due to M42. An additional, blue shifted, velocity component was seen on the spectra corresponding to the east and west limbs of HH269. This was present on all lines except [O II] and [O III]. A characteristic spectrum is shown in Figure 3.16. The component for Hα is badly blended with the nebular emission due to the great thermal width(25 km s⁻¹) of the low mass H I atoms. We know from the low-resolution spectra and HST images that the [O III] emission from HH269 is weak. The absence of detected [O II] components was surprising, since the low-resolution spectra indicated that [O II] was strong. Perhaps the answer to this lies in the [O II] emission being of low-velocity relative to the principal ionization front. A blueshifted component at -22.5±2.4 km s⁻¹ was seen in five lines(He I 5876, [S II]6717 and 6731, [N II]6548 and 6583Å) for the west limb and at -13±1.4 km s⁻¹ in the two [N II] lines for the east limb. The coincidence of these blueshifted components with the positions of the knots in the shell is clear evidence for these knots approaching the observer.

The high-resolution spectra combined with the previous proper motion study can give a thorough description of the kinematics of HH269. Our high-resolution spectra indicate that the east and west knots of HH269 have heliocentric velocities of -13 and -22.5 km s⁻¹, respectively. O'Dell et al.(1993a) argue that the high-ionization component seen here at +15.6 km s⁻¹ represents the main layer of emission, with the low-ionization component representing the motion of the actual ionization front
Figure 3.16 High-resolution [N II] spectrum on the west limb of HH269. The red velocity component is due to the primary ionization front of the Orion Nebula and the blue shifted component is due to HH269 (after O'Dell et al 1995).
of the blister, which is determined from more extensive data to be at 28±2 km s⁻¹, an argument expanded upon by O'Dell(1994). The ionization front is not moving with respect to OMC-1. This means that the east and west components are moving 39 and 49 km s⁻¹ blueward with respect to OMC-1 and its associated star cluster, which has the same velocity as the cloud. Cudworth(1977) measured three bright feature on HH269 including the west knot. His result for the west knot is \( \mu_\alpha = -2.7\pm0.2; \mu_\delta = 1.1\pm0.4''/\text{century} \), which corresponds to a tangential velocity of 61±7 km s⁻¹. Combined with the radial velocity, the spatial velocity of the west knot of HH269 would be 78 km s⁻¹ at a direction 38° with respect to the line of sight of the observer, blueward. These velocities are quite similar to the values of velocities of HH203 and HH204. Although HH269 has many of the characteristics of an HH object, such as low-ionization, high proper motion and radial velocity, its elliptical shape with no obvious source near the middle makes the association difficult. We looked for corresponding infrared features in J band, H₂, and [Fe II] images of Orion by Allen and Burton(1993). In the J band only a faint outline of the entire ellipse could be seen and nothing was present in the [Fe II] image. However, the eastern knot was very bright in the 2.1 micron line of H₂ and was elongated east-west for several arcseconds. There was a much fainter extension of this linear feature all of the way to J&W352(Jones & Walker 1988), which is 11'' east of the eastern knot. J&W352 is also the variable LQ Ori, which Herbig and Terndrup(1986) spectroscopically classify as K2V. Recent photometry by Prosser et al.(1994) place this star well above the main
sequence and at a position corresponding to a pre-main-sequence star of a contraction age of about 300,000 years. An association of HH269 and J&W352 is difficult to assess since there are many bright arcs and linear features in the inner part of Orion. What is more puzzling is that there are a couple of HH269-like features located to the east and west of HH269. They look much like HH269 both in shape and in size. The driving source of these similar objects could be the same or similar ones. However it remains a mystery at this time. Hopefully further studies of this region will resolve these questions. This study on HH269 has been published (Walter et al. 1995).
Chapter 4

Other High Velocity Systems in the Orion Nebula

As previous studies have shown, the vicinity of the Trapezium cluster (Meaburn 1988, Meaburn et al. 1993, Massey & Meaburn 1993, Massey and Meaburn 1995) and the vicinity of Herbig-Haro 202 (Meaburn 1986) are regions rich in high-speed ionized flows. These flows have spatial scales from sub-arcsecond to arcminute, and the velocity of the flows range from tens of kilometers per second to over a hundred kilometers per second. We used the Coudé Feed system at Kitt Peak National Observatory to do a high resolution spectroscopic survey of the two regions at the wavelength of $[\text{O III}]\lambda5007$, because most of the materials present near the Trapezium cluster are highly ionized. As shown in Figure 2.8, the long slits of length of ~3' (projection on the sky) were evenly placed both east-west and north-south covering the regions of interest. In this way, both unresolved flows fell into the slit and an integrated picture of large scale motions could be investigated. Figure 4.1 is a sketch of the high velocity features we will discuss in this chapter, which can be used as a finding chart.
Figure 4.1  The high velocity features in the vicinity of the Trapezium cluster and HH202.
4.1 High Velocity Flows in the Vicinity of the Trapezium

4.1.1 Velocity Features Associated with Compact Knots

Although originally the slit spectra were intended to survey larger scale high velocity structures, some of the compact sources in the vicinity of the Trapezium happened to fall in our slits, and the striking unresolved high velocity features associated with them which are worth reporting. They flow at least as fast as 150 km s\(^{-1}\).

A new class of objects in this region was first detected by Laques and Vidal (1979) as unresolved emission line objects which they interpreted to be "partially ionized globules" (PIGS). Subsequent high resolution VLA maps of the Trapezium region yielded many additional sources besides the six objects discovered by Laques and Vidal (1979) as marginally resolved thermal ionized sources of high surface brightness (Churchwell et al. 1987, Garay et al. 1987). The interpretation of these objects as circumstellar material around a young star was argued by Churchwell et al. and by Meaburn (1988) from the marginally detected presence of a few stars in some of the objects. It was, however, the improved resolution of the HST (even in its pre-refurbishment form, O'Dell et al. 1993b) which made identification of their true nature possible. These objects are now called proplyds, a type of object defined as a young star with circumstellar material rendered visible by being in or near an H II region and the term arises as a contraction of protoplanetary disk, which is probably what many of them are. This model was confirmed by the second, higher resolution observations with HST in this same region (O'Dell & Wen 1994) and by
the 11.7 and 8.8 \( \mu \text{m} \), 0.5" resolution imagery of Miles et al. (1994). In this region, the proplyds are seen through their external ionization by \( \theta^1 \text{C} \) Ori, the O type star which dominates the hydrogen photoionization process. In each case, the near side of the circumstellar material is photoionized by the O star and sometimes this ionization boundary extends around the circumference of the object. The objects are commonly distorted and those nearest \( \theta^1 \text{C} \) Ori are highly subtended, showing a bright cusp oriented towards the photoionizing star and possessing a tail facing away. Figure 4.2 shows the WFPC2 image of this region and the projection of our long slit positions on the sky.

There are six proplyds that fall in or are located close enough to our slit positions and all of them show high velocity features on [O III] spectra. We use the naming system of O'Dell & Wen (1994). The position, previous designations and the heliocentric velocities of the flows are summarized in Table 4.1. The actual spectra and contour plots of spectra can be found in Figure 4.3–4.7, where the positions of these objects on the spatial axis are indicated.
### Table 4.1
Position and Kinematics of Proplyds

<table>
<thead>
<tr>
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<td>141-302</td>
<td>5:35:14.11</td>
<td>-5:23:02.16</td>
<td>C</td>
<td></td>
<td></td>
<td>up to 50</td>
</tr>
<tr>
<td>157-323</td>
<td>5:35:15.71</td>
<td>-5:23:22.59</td>
<td>26</td>
<td></td>
<td></td>
<td>up to 50 + continuum$^d$</td>
</tr>
<tr>
<td>158-323</td>
<td>5:35:15.82</td>
<td>-5:23:22.50</td>
<td>11</td>
<td>5</td>
<td>488</td>
<td>up to 50 + continuum$^d$</td>
</tr>
<tr>
<td>160-353</td>
<td>5:35:15.98</td>
<td>-5:23:52.96</td>
<td>23</td>
<td></td>
<td>503</td>
<td>-30, up to 50</td>
</tr>
<tr>
<td>167-317</td>
<td>5:35:16.73</td>
<td>-5:23:16.63</td>
<td>6</td>
<td>2</td>
<td>524</td>
<td>up to 150</td>
</tr>
<tr>
<td>171-334</td>
<td>5:35:17.06</td>
<td>-5:23:34.02</td>
<td>3</td>
<td></td>
<td>538</td>
<td>160</td>
</tr>
</tbody>
</table>

$^a$ Felli, M. et al. 1993

$^b$ Laques, P. & Vidal, J.L. 1979

$^c$ Jones, B.F. & Walker, M.F. 1988

$^d$ 157-323 and 158-323 are unresolved neighboring objects.
Figure 4.2  Three color composite WFPC2 image of the Trapezium region with the slit positions of our spectroscopy overlaid. [O III] is coded as blue, Hα is coded as green and [N II] is coded as red.
Figure 4.3  [O III] slit spectra of slit position A6. The vertical axis is the angular distance from $\theta^1$B("") and the horizontal axis is the heliocentric velocity (km s$^{-1}$).

It is a significant fact that all of the proplyds observed are associated with high velocity features. Of the six objects we sampled, receding velocity components are found for all of them with heliocentric velocity ranging from 50 km s$^{-1}$ to as high as 160 km s$^{-1}$. These red-shifted "spikes" in position-velocity arrays also have a continuous range of radial velocities extending back to the velocity of main nebular material, which would indicate some acceleration of the outflowing jet material. Massey & Meaburn's (1995) observed high velocity flow associated with 158-323 which would argue that the high velocity feature appearing at our slit position B9 is most likely associated with object 158-323 rather than 157-323. The blue-shifted "knot" feature with an approaching heliocentric velocity of 30 km s$^{-1}$ on p-v array B6 is slightly
Figure 4.4  [O III] slit spectra of slit position B4–B8. All the vertical axes are heliocentric velocities (in km s\(^{-1}\)) and all the horizontal axes are the angular distance (") from the right ascension of \(\theta^1\)C Ori
Figure 4.5  [O III] slit spectra of slit position B9–B12. All the vertical axes are the heliocentric velocity in km s\(^{-1}\). Horizontal axes for B10–B12 are angular distance(\('\)') from the right ascension of \(\theta^1\)B Ori while from the right ascension of \(\theta^1\)B Ori for B9.
Figure 4.6 [O III] slit spectra of slit position B13–16. All the vertical axes are the heliocentric velocity in km s$^{-1}$. All the horizontal axes are angular distance($''$) from the right ascension of $\theta^1$B Ori.
Figure 4.7  Contour plots of slit spectra which contain the flows of the proplyds. In order to show the fainter features, the natural logarithm of the brightness of the spectra are used.
displaced to the east of 160-353 and is suspected to be associated with the [O III] strong arc feature east of the proplyds. In this region similar approaching features associated with bright [O III] emissions are also found to the west of 160-353 and to the south on B5. These have been also observed by Castañeda (1987).

Various mechanisms are possible explanations for the high velocity flows associated with proplyds. It is known that proto planetary disks surrounding YSOs may be capable of collimating internal outflows to generate the bi-polar jets that would be ionized later on. In the vicinity of θ1C, the ionization is most likely due to the Lyman radiation from the star. However, our spectra show that receding flows dominate for the six observed objects. The flows look more “mono-polar” rather than “bi-polar”. Considering the fact that θ1C is an O6 star with a stellar wind of velocity of 510 km s\(^{-1}\) (Prinja et al 1990), the outflow from proplyds close to θ1C could be deflected by the the stellar wind from θ1C. The preference of the receding flows could be achieved if these observed proplyds are located on the far side of θ1C. This can be one of the mechanisms responsible for the “mono-polar” flow. Alternatively, if the outflows from the proplyds’ are less important than the stellar wind momentum, the evaporated ionized material off the surface of the proplyds’ could be accelerated by the stellar wind and produce “mono-polar” like flows. Again the preference of the receding flows can be explained if these observed proplyds are located on the far side of θ1C. The “cometary-tail” morphologies of most of the proplyds in this region would support these pictures. Generally speaking, except 158-323, our four observed
objects' flow velocities are inversely proportional to their projected distance to \(\theta^1\text{C}\). This indicates the interaction of material from proplyds' with the stellar wind could play an important role in the formation of the high velocity features associated with these proplyds'.

### 4.1.2 Large Scale Velocity Features

We report the discovery of a circular velocity feature near the Trapezium cluster. The center of this "disk" feature is located at \(\alpha = 5^h 35^m 14^s.0; \delta = -5^\circ 23^\prime 25^\prime\) (2000) and the diameter of the disk is \(\sim 1\). This "disk" feature was first noticed on our \([\text{O III}]\) spectra. On both horizontally and vertically placed slit spectra, this feature appears to have a receding velocity and the velocity is almost constant across the disk. The heliocentric radial velocity of the disk extends from the major nebula velocity to \(\sim 50\text{ km s}^{-1}\). On these spectra the boundary of this disk are well defined for a good fraction of the circle. For example, the western edge of the disk corresponds with the receding velocity feature on B6, B7 and B8 (Figure 4.4), where the velocity feature ends at 70", 60" and 50" west of \(\theta^1\text{C}\), respectively. For slit position B9–B12 (Figure 4.5), the western end of the disk are entangled with some other high velocity features which will be mentioned in the next section, so the boundary is not obvious on these spectra. Similarly, the eastern end of the disk are not as obvious as the western end due to the complication from other high velocity features, however, on position B6–B8, the eastern boundary of
the disk is detectable. Of the vertical slit positions, B19–B22(Figure 4.9, 4.10) show good spatial correspondence of both the northern and southern ends of the receding velocity feature with the boundary of the disk. On B19, the northern part of the disk doesn’t show the high velocity feature and this can be explained by the imagery. On the HST WFPC2 image of this region(Figure 4.8), this 1’ disk feature shows stronger [O III] emission compared with neighboring regions with a well defined dark lane as the boundary. Along the slit position B19, from the northern edge of the disk, there is an intruding “finger like” dark feature extending to the south. This feature corresponds to the invisible part of the disk on B19.

The true nature of this [O III]-strong disk remains a puzzle at this stage. Though based on the fact that the boundary of the disk is defined by a dark lane and the intruding “finger” makes the velocity feature invisible, we would argue that this disk feature is associated with a lower-extinction region which makes the receding velocity feature visible through a “hole”. This “hole” could well be in the neutral “lid” in the foreground of the nebula where most of the extinction comes from for this region. Further theoretical work is needed in understanding the cause of the “hole” and where on the line of sight the receding velocity is located. Since the highly ionized material has a velocity that is effectively going into the molecular cloud(which is moving 26 km s⁻¹ away from us), it is hard to imagine that the feature is located on the main ionization front.
Figure 4.8  Field of view of the region west of the Trapezium. Three color composite of HST WFPC2 image, [O III] is coded as blue, Hα is coded as green and [N II] is coded as red. Spectroscopic slit positions are superimposed.
Figure 4.9  [O III] slit spectra of slit position B18–B21. All the vertical axes are angular distance (") from the declination of θ¹C Ori and all the horizontal axes are the heliocentric velocities in km s⁻¹.
Figure 4.10  [O III] slit spectra of slit position B22-B25. All the vertical axes are angular distance(") from the declination of θ¹C Ori and all the horizontal axes are the heliocentric velocities in km s⁻¹.
Figure 4.11  [O III] slit spectra of slit position B26–B27. All the vertical axes are angular distance("") from the declination of $\theta^1$C Ori and all the horizontal axes are the heliocentric velocities in km s$^{-1}$. 
4.2 The High Velocity System Near Herbig-Haro202

HH202 is a peculiar HH object compared with others in the sense that it is located the closest to the Trapezium cluster and complicated high velocity systems have been found in its vicinity, that may or may not be associated with it. It was first discovered and studied by Cantó et al. (1980a). As a rather large object, it has two bright knots with strong emissions from low ionization species such as [S II], [N II], etc. The heliocentric radial velocity of HH202 is as high as \( \sim 60 \) km s\(^{-1}\) for most of the ions (O'Dell et al. 1991). The nature of this object has been interpreted in different ways by Meaburn (1986) and O'Dell et al. (1991). Meaburn suggested that HH202 could either be a collimated flow, shock ionized by the wind from a local source, with a surrounding pressure driven bubble radiatively ionized by the ultraviolet radiation of the general field from the OB stars in the Trapezium cluster; or is some manifestation of the general, bi-conical, molecular outflows from the BN source. Their [O III] spectroscopic study of this region indicated that there is an [O III] emitting region extending over a half-disk of radius 20\(^\prime\), with its east-west chord on HH202, that has similar negative velocity component of -54 km s\(^{-1}\). O'Dell et al. interpreted the southern knot of HH202 as a bow shock due to the interaction of a collimated high-velocity jet with the ambient gas originating from the ionization front of M42. The high and low velocity component in their spectra were explained as the bow shock out ahead of the jet and the "Mach disk" which is a compression of density in the jet. This section will report detailed spectroscopic study of [O III] line
of HH202 and its surrounding region and to show that there are actually two high velocity systems in the vicinity of HH202.

On Figure 4.8, one can easily find an [O III] (coded blue in the image) enhanced region starting from the west end of the double knots of HH202 extending approximately 20″ to the west of the HH202. Also to the south of HH202, there is another [O III] enhanced region extending from the western edge of the “bright-disk” discussed in the previous section to the west with an incomplete round shaped boundary at about 10″ west of HH202. Both of these two features are found to have corresponding high velocity spectral features in our [O III] spectra. We designate these two extended high velocity features as HH202w and HH202s respectively.

HH202w and HH202s show up in our [O III] spectra as complex approaching velocity components on both horizontal and vertical slit positions. The southern boundary of HH202w appears on B12 as a shell-like feature with the high velocity end located to the south of the HH202 knots, and the feature extends all the way to ~20″ west of the knots where the velocity of the flow reduces to the nebular velocity. On B13, HH202w separates into three high velocity knots on the position-velocity diagram. The highest velocity knot (~45 km s⁻¹) is located to the immediate west of HH202 knots and another knot with lower velocity (~25 km s⁻¹) is located a few arcseconds west. A third knot with even lower velocity (~5 km s⁻¹) is located about 20″ west of HH202 knots. Going further north, HH202w can be identified as two high velocity flows on B14, one of which is located immediately to the west of HH202 knots.
again with velocities extending up to -40 km s\(^{-1}\), while the other one is located about 10\(^{\prime\prime}\) west of the first one with similar velocity magnitude. HH202w has disappeared on B15. On the vertically placed slit spectra, HH202w appears on B24 through B27. Generally the velocity reduces westward. On B24, the high velocity knot is located near the southern knot of HH202, and has a heliocentric velocity around -40 km s\(^{-1}\).

On B25, two separate high velocity knots are found. One of them is located to the west of the HH202 southern knot and the other one is a few arcseconds north, with velocities of ~-40 km s\(^{-1}\) and ~-20 km s\(^{-1}\). On B26(further west), two extended high velocity knots are found right on HH202w, with velocities up to -35 km s\(^{-1}\). One can still identify the diminishing velocity feature on B27 while HH202w has disappeared on B28. HH202s also corresponds to complex high velocity approaching flows on our spectra. On B11, the high velocity feature cross at ~20\(^{\prime\prime}\) region to the south of HH202. HH202s shows up more obviously on the vertical slits. The "shell-like" feature on B23 corresponds to HH202s. On B24, the HH202s region looks like a "half-shell" feature. On B25, only a lower velocity feature appears at the edge of HH202s, while it has disappeared on B26.

The nature of this complex high velocity system near HH202 is not yet revealed at this stage, although suggestions could be made through our data. Those "shell-like" features indicate that these features could be pressure driven bubbles being radiatively ionized by ultra-violet photons from the Trapezium cluster. Although the driving mechanism of the "bubble" is yet to be determined.
Chapter 5

Summary and Future Work

This work concentrates on the high velocity flows in the central region of the Orion Nebula. It has improved our understanding of Herbig-Haro objects, kinematic properties of proplyds and large scale flows in this active star-forming region.

We have been able to use the high resolution HST WFPC2 images to determine the proper motions of some of the HH objects (northern group) for the first time. Combined with our high spectral resolution échelle spectra, complete kinematic information has been obtained for these HH objects. Furthermore, a bow shock model has been applied to predict the spectral profile of emission lines from bow shocks. The prediction can be well fit with the observation so that the nature of these HH objects is proposed to be bow shocks. The relationship of these bow shocks with the infrared source (IRc2) buried in the molecular cloud was confirmed. The “interstellar bullet” model is favored for this group of objects. Some arguments about the forming of these “bullets” have also been discussed.

The high spectral resolution spectroscopy has also been combined with other imagery as well as low resolution spectra in studying the kinematics of two HH objects with larger spatial scales (southern group). The physical properties of HH203, HH204 and knot C as well as the newly found HH-like object HH269 have been investigated.
The kinematics of several proplyds in the vicinity of the Trapezium cluster has also been covered. Suggestions on their spatial location and the possible driving mechanism of the flow associated with them have been discussed. A couple of large scale high velocity systems have been discovered on our spectroscopic mapping of the central region of the Orion Nebula. Spectroscopic data on these systems are presented.

Further theoretical work is needed in modeling the Herbig-Haro objects in the Orion Nebula. The conflict between the observed spatial velocity and the bow shock model suggested velocity needs to be reconciled. The driving source(s) of HH203 and HH204 are yet to be found. The determination of the nature of Knot C requires further observation of proper motion as well as further theoretical work. As a newly found object, HH269 has the most peculiar shape and several objects nearby with similar shape makes the nature of this class of objects a puzzle. Although various models for the flow from proplyds exist, further theoretical work about the proplyds in the environment of strong stellar wind is needed in revealing the most reasonable model. The formation of the receding “disk” feature should be investigated. Other observations such as the Fabry-Perot spectroscopic study and theoretical work in the interaction of high velocity flows with ambient materials are needed for understanding the nature of these large scale structures near HH202.
In summary, this work is observation-oriented with some theoretical discussions on various topics. More detailed theoretical work needs to be done to explain all the observed high velocity phenomena in the Orion Nebula.
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