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I. INTRODUCTION

This thesis addresses itself to one of the most fascinating astronomical phenomena yet discovered by man. Since their first detection in 1967 (Hewish et al. 1968), pulsars have absorbed the attentions of astronomers and captured the imaginations of astrophysicists the world over. Few astronomical phenomena in history have been subjected to such intensive investigation.

In section II, the current state of knowledge of this phenomenon is described through a brief review of what has been learned about the sixty-odd pulsars discovered so far. Two of the known pulsars, and a third object which may be closely related to the pulsar phenomenon, have been observed in a series of balloon flights which is discussed in section III. The methods and instruments employed in these hard X-ray observations at balloon altitudes are described in section IV. Section V discusses the extensive data manipulation procedures required to extract information about the observed objects.

Described in section VI, with the other results of these measurements, is an exciting new finding: the apparent
detection of pulsed hard X-rays from the Vela pulsar, PSR 0833-45. This object previously had not been observed at any frequency above the radio region. Also reported is a new, early measurement of the period of the Crab Nebula pulsar, PSR 0531+21.

Section VII presents a review of the X-ray properties, as determined by other investigators, of the objects which are the subject of section VI, and uses this review as a context in which to examine the relevance of the present measurements to currently accepted theories.

The results are summarized in a final concluding section, and several appendices are included in order to amplify certain matters treated only briefly in the text.
II. THE PULSAR PHENOMENON

The measurements which led to the discovery of the first "rapidly pulsating radio sources" were made during the summer of 1967, nearly ten years after the first powerful radio telescopes had appeared on the astronomical scene. Just as the discovery of the first extraterrestrial radio sources was an accident, so was the new phenomenon of pulsating sources discovered in a search for quite another phenomenon. The equipment at the Mullard Radio Astronomy Observatory, Cambridge, had been assembled for the purpose of investigating and exploiting the properties of interplanetary scintillation which is caused by inhomogeneities in the solar wind. Hence it was that the group at Cambridge was the first with experimental apparatus capable of detecting this new class of astronomical objects.

The phenomenon first appeared as "interference" in the records obtained by the Cambridge group during summer 1967. By December, they had become sufficiently annoyed with the interference that their attempts to get rid of it had led them to the discovery that the "worst" interference was periodic and originated from a fixed celestial region.

Hewish, Bell, Pilkington, Scott, and Collins (1968) reported their discovery to the scientific community in the
February 9 issue of *Nature Magazine*, where they detailed their findings regarding the strongest (which was to become known as CP 1919) of the four objects they had discovered. Two weeks later, Davies et al. (1968) at Jodrell Bank confirmed the observation of CP 1919 and reported further detailed properties of the unusual object.

That the imaginations of theorists were ready to answer this new challenge became evident with the appearance in March of the first two theoretical discussions of the new object, and *Nature* became the forum for the investigation of this exciting phenomenon which was termed the *pulsar*. A rapid pace of two or three new journal articles each week was established and persisted for many months. Most new experimental findings were announced by International Astronomical Union (IAU) Circular or telephone. (In fact, the use of the medium of the IAU Circular persists to the present time, with the most recent pulsar finding [IAU Circ. No. 2368] pertaining to measurements of the optical pulsar in the Crab Nebula).

The Cambridge group announced the locations of their other three objects in April (Pilkington et al. 1968); and by September 1968, nine pulsars had been discovered. The Cambridge group had found two more (Cole and Pilkington 1968);
a group at the Harvard College Observatory (Heguenin et al. 1968) had found another northern hemisphere source; and the group at the Mongolo Radio Observatory in Australia (Turtle and Vaughan 1968) had found two pulsars in the southern skies.

A word of explanation regarding the classification scheme is needed. The name given to a pulsar denotes both its celestial location and the observatory at which it was discovered. Hence CP 1919 was discovered by the Cambridge group and has a right ascension of 19h19m. Other observatory designations include: HP - Harvard College Observatory, MP - Mongolo Radio Observatory, and NP - National Radio Astronomy Observatory. A more rational scheme, suggested by Turtle and Vaughan (1968), employing a standard prefix PSR (for pulsar) followed by the (1950) values of right ascension and declination, seems to be gaining favor. Hence CP 1919 becomes PSR 1919+22, and NP 0532 becomes PSR 0531+21.

The most remarkable property of this new class of objects was the very accurate timing of their radio pulses. Figure 1 shows pulses from a typical radio pulsar. The initial findings of Hewish et al. (1968) indicated an accuracy of better than 1 part in 10^7 and consequently demanded a comparable accuracy of the theories put forth to explain
the phenomenon. An astronomical scale involving stellar masses seemed absolutely necessary, and hence opened up the possibilities of stellar pulsation, stellar rotation, and orbital motion (as in binary star systems).

Early theoretical discussions centered on the question of the clock mechanism and favored some type of pulsation in white dwarf stars. The determining criteria, aside from the need for inherent stability, were the range of pulsation frequency and the magnitude of this frequency. The first four pulsars had pulsation periods of 0.25, 1.19, 1.27, and 1.34 seconds. While the fastest period seemed to push white dwarf pulsation theory to its limit, the relatively narrow range of periods seemed accounted for by this theory.

It was the discovery by Staelin and Reifenstein (1968) in November, 1968, of two pulsars near the Crab Nebula that spelled the beginning of the end for the white dwarf pulsation theory. The Vela pulsar PSR 0833-45 had already been found (Large et al. 1968) to have a period (~89 milliseconds) much shorter than all others, but NP 0532 was found (Comella et al. 1958) to have a period of only 33 milliseconds and to be associated with the Crab Nebula. The other pulsar near the Nebula (NP 0527) was found (Zeissig and Richards 1960) to have a period of more than 3.75 seconds. Hence the slowest
FIGURE 1

(see page 8)

Fast galvanometer recording of single pulses received from pulsar CP 1133. These data were taken from Lyne and Smith (1968).
and fastest pulsars (fortuitously located within 2 degrees of one another) spanned a period range of more than two orders of magnitude. The pulsation theory in which the period of oscillation is tied closely to the structure and composition of the star, could not account for this dynamic range. Furthermore, only a rotating neutron star could account for the fast period of NP 0532 without additional complications like rotational instability or unbelievable quantities of gravitational radiation. Another finding which helped tip the balance in favor of a rotation theory was the discovery that some of the pulsars (the faster ones) were very gradually slowing down. Pulsation theory is at a loss to explain this effect, while it is a natural consequence of rotation.

Gold (1968) was among the first to point out that a rotating neutron star met all the criteria for a theory of pulsars. The theory predicted the slowing down of the pulse repetition rates and the existence of pulsars with faster (than the 0.25 second period discovered for one of the original four pulsars) periods. It was not long before the theory scored successes on both these points (Gold 1969), with the result that this theory is now accepted nearly universally.

The discovery by Cocke, Disney and Taylor (1969) of optical pulsations from the Crab Nebula pulsar moved other
observers to search for the pulsar at shorter wavelengths. Four groups, in rapid succession in the spring of 1969, announced successful detection of X-ray pulsations. The results of Fishman, Harnden, and Haymes (1969a) were unique in that they pertained to the properties of the pulsar at an earlier epoch, namely 1967 June 4. The measurement of the pulse repetition period at a point nearly two years previous in time permitted an improved estimate of the time derivative of the repetition period.

Since the discovery of the optical output of NP 0532 (or PSR 0531+21), the Crab Nebula pulsar has dominated the pulsar scene. The optical emissions have permitted an improved timing accuracy and have put the pulsar's time behavior under very close scrutiny. Errors in pulse arrival times are counted in microseconds, and period determinations are to within fractions of a picosecond. Yet NP 0532 is not the only pulsar worthy of special note.

In March, 1969, Radhakrishnan and Manchester (1969) and Reichley and Downs (1969) independently observed the Vela pulsar PSR 0833-45 to undergo an apparently abrupt decrease in period. In the interval between 1969 Feb 24 and 1969 Mar 3 the period seemed to have changed by ~200 nanoseconds. This event, and subsequent smaller discontinuities observed in
the Crab pulsar's behavior, have led several authors to discuss models in which a central pulsar has one or more planetary companions (cf., Michel 1970). Recently (Reichley and Downs 1971a) another "period jump" has been observed in Vela; this second abrupt decrease apparently occurred between 1971 August 21 and 1971 September 4. Hence the Vela pulsar now has two periodicities: the pulse repetition period of \( \sim 89 \) milliseconds, and the period-jump recurrence rate which has a time between jumps of \( 2.50 \pm 0.03 \) years.

A wealth of data exists for the radio pulsars, over sixty of which are now known. Detailed pulse structure, subpulse periodicities, polarization measurements, and the pulse "nulling" phenomenon are a few of the many properties now recognized and regularly investigated. Period-slowdown rates have been measured for about one third of the pulsars. The host of properties which must be explained by the ultimate pulsar theory is truly formidable. Pulsars appear to be in a realm not only of the unfamiliar neutron star but also of the vast complexities of plasma physics.

Recently, high energy astronomy has had some interesting things to say about pulsars. Evidence for the detection of gamma rays (energies \( >50 \) MeV) from the Crab Nebula pulsar has accumulated almost to the point of believability (see,
e.g., Kinzer et al. 1971). The X-ray astronomy satellite Uhuru has apparently discovered an X-ray pulsar (Giacconi et al. 1971) which is not known to be pulsating in the radio region. Both of these findings place still greater demands on the theorists' ability to understand the pulsar phenomenon.
III. BALLOON FLIGHT OBSERVATIONS

The initial success of the Rice University Gamma-Ray Astronomy Group (RUG-RAG) at detecting pulsed emissions from the Crab Nebula led to the consideration of a more extensive program of pulsar observations. Several possibilities existed, but the most promising object seemed to be the Vela pulsar, PSR 0833-45, with its second-fastest period of ~89 milli-seconds. Plans were made to observe this object. In addition, still earlier data on the Crab Nebula were available from a balloon flight in 1966. These data have also been reexamined for temporal variations.

At the time of the discovery of X-ray pulsations from the pulsar in the Crab Nebula, RUG-RAG was preparing for an observation of the constellation of Cygnus. It was felt that the intense X-ray source Cyg X-1 might also have interesting temporal characteristics. Hence, accurate clock pulses were included as part of the data recorded during that flight so they could later be used in a temporal analysis of the X-ray data.

This thesis presents an analysis of data from the four balloon flights listed in table I, which summarizes the pertinent details regarding the flights. The basic instrument employed in all four flights was a scintillation crystal of
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Note: time and dates are Universal Time
NaI(Tl) which is depicted schematically in figure 2. The two earliest flights were conducted before this work on pulsars began and were intended to observe the time-averaged gamma-ray emission from the Crab Nebula. The 1969 flight too was primarily an attempt to make a time-average measurement, though allowance was made for the possible existence of temporal variation. In contrast to the first three flights, the Vela-viewing portion of flight 1970-4 was executed solely for the purpose of observing the Vela pulsar.

The detection of light pulses from the Crab Nebula (Cocke, Disney, and Taylor 1969) had immediate impact not only on other experimentalists, but also on the theorists who had been trying to explain the unusual radio emissions of pulsars. The problem grew still more complex with the subsequent detection of X- and gamma-ray emissions from NP 0532. While such broad-band pulsar observations may be detrimental to particular theories (i.e., the wrong ones), the argument in favor of the widest possible range of observations is an overwhelming one. The fact that a very vigorous optical search for pulsar PSR 0833 has so far been unsuccessful (see e.g., Kristian 1970) is all the more incentive for attempting observations at higher photon energies.
FIGURE 2
(see page 17)

Schematic diagram of the NaI scintillation crystals used for the Gammascope II detector. The well-shaped guard crystal provides charged particle rejection and surpresses Compton events through the use of an active, anticoincidence technique. The plastic scintillator rejects charged particles in the forward direction but is transparent to gamma rays. Six phototubes (RCA 8054) are used to view the guard crystal, and three others (RCA 6199) detect events in the plastic scintillator. The full-width-at-half-maximum acceptance cone is 24° wide (i.e., 24° FWHM beamwidth).
GAMMASCOPE II DETECTOR

FIGURE 2
IV. EXPERIMENTAL APPARATUS AND TECHNIQUES

A. The Basic Instrument

When the Rice University Gamma-Ray Astronomy Group (RUG-RAG) was formed in 1965, an instrument (later to become known as Gammascope II) was designed and built (see Craddock, 1967). Essentially the same instrument has been used in all the observations reported in this thesis. The acceptance angle, or beam width, of the instrument is $24^\circ$, full width at half maximum (FWHM).

The photon energy region explored by RUG-RAG is sometimes called the hard X-ray, rather than the gamma-ray region. The overlapping terminology merely reflects the fact that an overlap indeed exists in nature: the X rays produced by certain atomic transitions are actually more energetic than some gamma rays which result from nuclear transitions. In the earlier balloon flights, the gamma-ray detector was designed to make observations in the energy range from $\approx30$ keV to $\approx500$ keV; the more recent flights have extended the upper threshold to $\approx1$ MeV.

Photons in the low-energy gamma-ray region (i.e., below $\approx10$ MeV) interact with matter through three primary processes: the photoelectric effect, Compton scattering, and pair production. The nature of these interactions is such that the
range (measured in gm cm\(^{-2}\)) of gamma-ray photons in matter is roughly independent of the material. There are, however, two rather unfortunate consequences of this fact for gamma-ray astronomy. Consider, for example, a 1-MeV photon which has a range of about 15 gm cm\(^{-2}\) in both lead and air. This means that the photon will penetrate about a centimeter of lead, making reflection impossible and even mere collimation very difficult. On the other hand, the linear range in STP air is less than a kilometer, which means that photons incident on the top of the earth's atmosphere will never reach the ground. The implications for gamma ray astronomers are obvious: they must be resigned to the building of crude, rather awkward instruments and must furthermore carry these instruments to an altitude of \(~40\) km. before being able to "see" the cosmos. The techniques used to operate the gamma-ray detectors at the required altitude are discussed in subsection D.

The operation of scintillation crystal detectors may be described as follows. An incident photon strikes the crystal (thallium activated NaI) and interacts by one of the three processes listed above. The intermediate processes differ according to the energy of the incident photon, but the end result is the same: some of the energy originally contained
in the incident photon is deposited in the crystal in the form of many excited-state atomic electrons. The final de-excitation process which removes the deposited energy from the crystal is the emission of optical photons, which are detected by photo-electron multiplier tubes (phototubes). The resulting electrical pulse from the phototubes is analyzed electronically (pulse height analysis) to obtain a measure of the amount of energy which was deposited in the crystal. The energy spectrum which results from this analysis is sometimes called an energy-loss spectrum in order to emphasize the fact that the total energy of the incident photon may not have been deposited in the crystal. Several possible intermediate processes can lead to energy escape from the crystal by means other than the final optical pulse. If the initial interaction is a Compton collision, the scattered photon may exit the crystal without further interaction. Whenever pair production occurs within the crystal, it is followed by the annihilation of the created positron. One or both of the 511 keV photons produced by the positron's annihilation may escape from the crystal without interaction. Also, when an electron de-excites through an X-ray producing transition to an inner atomic level, the X ray may escape if the event occurs near a surface of the crystal.
In the Gammascope II design (see figure 2) an anti-coincidence technique is used both to collimate the viewing direction and to suppress Compton events. When a coincidence occurs between an event in the central crystal and one in the guard crystal, the central crystal count is rejected. Such a count is presumed to be due to the detection in one crystal of a secondary photon which was produced by an event (also detected) in the other crystal. If the primary event is in the central crystal, the rejected count represents less than the total energy of the incident photon; while if the primary event is in the guard crystal, the count represents a photon from a direction outside the viewing region. These are obviously both unwanted effects. For counting rates normally encountered, the probability of chance coincidence in the two crystals is very slight (the chance coincidence rate is expected to be \(\sim 3\%\) of total count rate).

Central crystal counts which are not rejected are processed by the pulse height analyser (see figure 3). If the energy deposited is greater than the lower threshold, its pulse height is digitized (assigned channel number) and sent to the telemetry for transmission to the ground receiving and recording station. Energies greater than the upper threshold are tagged as "overflows" by assignment of a channel number
FIGURE 3
(see page 23)

Block diagram of the Gammascope IV-B pulse height analyzer. Not shown in the diagram is the capability of turning off (by radio command) either of the two detectors. The performance of the other detector is not affected when one is turned off, except for a slight gain shift caused by the change in input impedance (see Appendix C).
FIGURE 3  BLOCK DIAGRAM OF GAMMASCOPE IV B PULSE HEIGHT ANALYZER
of zero. The RUG-RAG experiments have all employed 128-channel energy analyzers.

B. Particular Differences

1. Flight 66-1

The balloon-borne system used for this flight was generally similar to the Gammascope II (GS II) gondola described below. The detector itself differed in that a narrow-angle collimator was afixed to the front of the detector. The collimator, composed of three anuli of plastic scintillator viewed by phototubes, was connected in anticoincidence (in parallel with the guard crystal) with the central detector. The arrangement called Gammascope I has been described by Craddock (1967) and resulted in a beam width of about 3½ to 4 degrees FWHM. The flight plan for this experiment called for an extended period of continuous viewing in the source direction, followed by a comparable time interval spent looking in directions away from known sources. Unfortunately a power failure occurred after about 2 hours of Crab Nebula observations and no background data were obtained at float altitude.

2. Flight 67-1

Ellis (1967) has made a detailed analysis of the data
obtained from flight 67-1, and these results have been published (Haymes et al. 1968a). The detector used was GS II-A, which as described by Glenn (1969) had a larger instrumental absorption (see Appendix C) than detectors subsequently employed. The narrow-angle collimator was not used on this or subsequent flights. The GS II gondola system was employed.

This flight proceeded according to the nominal flight plan until the hour angle drive circuitry failed after four hours of observations of the Taurus region. The flight plan provided for both source and background observation, in alternating ten-minute intervals, so that the data obtained prior to the failure were highly useful.

3. Flight 69-1

This was the final flight of the GS II balloon-borne system and, like most of the flights after 67-1, was virtually a textbook flight. Telemetry was noise-free throughout the 8-hour observation of the Cygnus region. The nominal aiming point of the GS II-B detector was the position of the X-ray object Cyg X-1. The results of an analysis of the time-averaged flux detected during this flight have been reported by Haymes and Harnden (1970).
4. Flight 70-4

As part of an attempt to develop a new gamma-ray telescope of improved sensitivity, RUG-RAG designed and constructed a new balloon-borne system, Gammascope IV. While the GS IV detector failed to meet expectations (see Harnden 1971), the gondola system worked quite well. In order to exploit the capabilities of the new system, the two GS II detectors (A and B models) were used simultaneously. (Subsequent to flight 67-1, detector GS II-A was modified to reduce the instrumental absorption and was maintained as a back-up instrument).

The balloon-borne system was redesignated GS IV-B and modified slightly to accommodate the dual-detector instrument more efficiently. The pulse height analyzer, which the two detectors shared, was modified to include an extra bit which identified X-ray counts as originating either in detector A or in detector B. The two detectors were placed on the common equatorial telescope mount with their axes in parallel alignment.

Shortly after the launch of flight 70-4, detector A became "noisy" and was turned off by radio command. The other detector, and the remainder of the telescope system, operated normally throughout the 17.5 hour flight. A discussion of
the detector A malfunction is given in appendix C.

C. Observational Technique

1. The Equatorial Telescope Mount

Because the use of equatorial telescopes in high energy astronomy is rather limited, and because all Rice observations have employed this type of pointing system, a description of the equatorial mount will be given here.

The equatorially mounted telescope is employed widely by ground-based optical astronomers because of the ease of operation. Once such a telescope has been properly aligned and pointed at an object, only one motion is required to keep the celestial object virtually motionless in the field of view. A simple rotation about the right ascension axis compensates for the earth's rotation and makes the sky appear stationary.

As can be seen in Figure 4, the right ascension or polar axis of the telescope must be aligned with the earth's rotation axis. This is accomplished by orienting the axis properly in the observer's horizon coordinate system; the telescope's polar axis has an elevation angle equal to the geographic latitude of the place of observation and an azimuth heading of due north (geographic). After the alignment is
FIGURE 4

(see page 29)

Schematic diagram showing proper alignment of an equatorial telescope mount.
THE EQUATORIAL TELESCOPE MOUNT

FIGURE 4
achieved, the observer need no longer concern himself with
the horizon coordinate system and is free to work in the
natural frame of the sky, i.e., the equatorial coordinate
system. An object of celestial coordinates \((\alpha, \delta)\) is acquired
by moving the telescope to a declination setting of \(\delta\) and an
hour angle of: hour angle = sidereal time - \(\alpha\). The sidereal
time of the place of observation is determined either by
an ephemeris calculation or by the observation of reference
stars.

The RUG-RAG telescope mount is aligned using two refer-
ence directions: the vertical and geomagnetic north. Prior
to launch, the polar axis is fixed at an elevation angle
equal to the mean geographic latitude of the predicted bal-
loons trajectory. Once the balloon has reached its float
altitude, the azimuth servo system is turned on; and this
system rotates the inner gondola (relative to the outer gondola)
until alignment is achieved with the geomagnetic field which
is sensed with a flux gate magnetometer. Geographic north
alignment is assured by introducing (prior to launch) an off-
set equal to the mean magnetic variation for the predicted
trajectory. Declination and hour angle settings, as well as
the hour angle rate of change, are determined by ground con-
trollers through the use of a radio command system.
2. Background Measurements

With the system as described above, the selected object would remain in the field of view continuously. While this is desirable for optical studies, gamma-ray observation time must be divided between source and background. In comparison with the high background or noise flux, the source or signal fluxes encountered in gamma-ray astronomy are rather weak. Consequently, for such low signal to noise ratios, the optimum division of time between source and background observations is one to one.

The background measurements must meet two conflicting criteria: (1) they must be made as close in time as possible and in a direction which is separated from the source-viewing direction by the least possible amount; whereas (2), they must be spatially far enough removed from the source direction that the object is removed from the field of view. Furthermore, since the gamma ray flux at balloon altitudes is noticeably dependent upon elevation angle (or equivalently, its complement, the zenith angle), background observations should be made at the same zenith angle as the source observations. These constraints may be visualized with the aid of figure 5, which is a view of the geocentric universe as seen by an outside observer. Z is the zenith point for an observer viewing a source object at S. The small circle drawn about Z is the locus of all points on the
FIGURE 5
(see page 33)

The celestial sphere as it would appear from "outside" the universe. The earth is at the center of the sphere, and point Z is the zenith point of an earthbound observer. Further details are discussed in the text.
FIGURE 5
sky which have the same zenith angle, ZA, as the point S. The point B has the largest possible separation from S; that separation is seen to be twice the zenith angle.

The zenith angle of a given object varies continuously from its maximum value, $ZA = 90^\circ$, when the source is on the horizon, to a minimum value at culmination (or upper meridian transit) of $ZA = |\lambda - \delta|$, where $\lambda$ is the latitude of the observer, and $\delta$ is the declination of the object.

A basic difficulty with GS II observations may now be understood. Objects which pass close to the zenith at transit can not be fully removed from the background observations unless point B is selected for the background. In fact, even point B is not adequate for objects such that $2|\lambda - \delta| < \frac{1}{2} \chi$ (beam width). As can be seen from tables II and III, the observation of Cygnus X-1 from Alamogordo is such a case; background observations obtained near transit during flight 69-1 are contaminated by the source. Yet the selection of point B for the background observations means that these observations will be spatially far removed from the source direction when the object is at large zenith angles (i.e., at times long before or after transit). Still a further difficulty is the fact that the gamma-ray background flux may have a slight azimuthal dependence in addition to the more
**TABLE II**

**GEOGRAPHIC POSITIONS* OF BALLOON LAUNCH SITES**

<table>
<thead>
<tr>
<th>PLACE</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraña, Argentina</td>
<td>31° 36' S.</td>
<td>60° 18' W.</td>
</tr>
<tr>
<td>Palestine, Texas</td>
<td>31° 47' N.</td>
<td>95° 42' W.</td>
</tr>
<tr>
<td>Alamogordo, New Mexico</td>
<td>32° 50' N.</td>
<td>106° 08' W.</td>
</tr>
</tbody>
</table>

*Accuracy of positions is estimated at ± 15 arc minutes.*
<table>
<thead>
<tr>
<th>OBJECT</th>
<th>EQUATORIAL COORDINATES (1950)</th>
<th>GALACTIC COORDINATES</th>
<th>REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab Nebula Pulsar</td>
<td>$05^h31^m31.46^s$ $+21^o58^m54.8^s$</td>
<td>$184.6^o$ $-5.8^o$</td>
<td>Minkowski (1968)</td>
</tr>
<tr>
<td>Cyg X-1</td>
<td>$19^h56.5^m$ $35.1^o$</td>
<td>$71.4^o$ $3.1^o$</td>
<td>Seward (1970)</td>
</tr>
<tr>
<td>Cyg X-3</td>
<td>$20^h30.9^m$ $40.9^o$</td>
<td>$80.0^o$ $0.7^o$</td>
<td>Seward (1970)</td>
</tr>
<tr>
<td>Vel XR-1</td>
<td>$8^h57^m$ $-41.2^o$</td>
<td>$263.3^o$ $2.9^o$</td>
<td>Seward et al. (1971)</td>
</tr>
<tr>
<td>Vel XR-2</td>
<td>$8^h42^m$ $-45.0^o$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSR 0833-45</td>
<td>$8^h33^m39.09^s$ $-45^o00.5^s$</td>
<td></td>
<td>Chiu et al. (1971)</td>
</tr>
<tr>
<td>Puppis A</td>
<td>$8^h20^m30^s$ $-42^o50^o$</td>
<td>$260.4^o$ $-3.4^o$</td>
<td>Milne (1970)</td>
</tr>
<tr>
<td>Vel X</td>
<td>$8^h32^m$ $-45^o00^o$</td>
<td>$263.4^o$ $-3.0^o$</td>
<td>Milne (1970)</td>
</tr>
</tbody>
</table>
pronounced zenith angle effect. This makes background observations at widely removed azimuth values even less satisfactory.

In spite of the above objections to the selection of point B as the point for background measurements, the RUG-RAG method employed on nearly all previous flights did in fact use that point. Normally the gondola system was configured to alternate between points S and B automatically at intervals of about 10 minutes. The change from viewing in direction S to viewing in direction B is easily accomplished by a rotation, by 180° in azimuth, of the entire telescope mount. In the B-mode, the polar axis of the telescope is no longer parallel to the earth's rotation axis.

The Vela observations of flight 70-4 differed from this usual method in that the pointing mode was controlled by radio command. Only three 10-minute intervals were spent viewing point B, while the remainder of the 5-hour observation was spent tracking point S (i.e., the pulsar) in its diurnal motion across the sky. Pulsars, with their short duty cycles (the ratio of "on-time" to the total pulsation period), provide a convenient means for measuring the background and the source in the same direction.
D. Balloon-borne Telescope Systems

Flights 67-1 and 69-1 employed the GS II balloon gondola which is shown in figure 6. The GS I system used for flight 66-1 was virtually identical to GS II except for minor mechanical differences necessitated by the use of the heavier, collimated detector. This basic system has been discussed in detail by Craddock (1967) and Ellis (1967) and will not be described here.

Though numerous improvements, over GS II, were incorporated in the design of the GS IV balloon system, there is only one major difference from the standpoint of observational capability; GS IV has the ability to view several different celestial objects during a single flight lasting as long as 40 hours. This versatility comes about through the use of a telescope mount with a variable declination setting and a multiple speed, bi-directional right ascension (or hour angle) drive. GS II had neither of these features and consequently had no use for a prolonged endurance capability, since the practical viewing time for a single object is limited to the eight to ten hour period during which the object is at zenith angles less than approximately the arc secant of two.

The GS IV-B system is shown in figure 7 and differs
FIGURE 6
(see page 40)

The Gammascope II balloon-borne telescope system. Some description is included in the text, but see Craddock (1967) for complete details.
The Gammascope IV-B balloon-borne telescope system. Slight differences between this system and the GS IV-A system are described in the text. See Harnden (1971) for a description of the GS IV-A system.
GAMMASCOPE IV-B
BALLOON-BORNE SYSTEM

FIGURE 7
only slightly from the GS IV-A system described by Harnden (1971). The cage-type polar axis of version A was replaced by a more versatile, and lighter, yoke-type axis. Also, the variable latitude and magnetic variation assemblies were removed since the pointing tolerances for the 24° beamwidth detector did not require such capabilities. The electronics were modified slightly: the star sensor was removed, an eighth bit was added to the PCM word of the pulse height analyzer, additional power supplies were added for the second detector, and a manual pointing-mode control capability was implemented. The circuitry of the two detectors was designed so that, should one become inoperative, it could be turned off and would not affect the operation of the other instrument. As mentioned earlier, this provision saved flight 70-4 from disaster.

E. Telemetry Systems

All of the flights described in this thesis used similar telemetry systems. A single FM transmitter was modulated with the output of a mixer amplifier, the inputs to which came from several voltage controlled oscillators (VCO's). A typical arrangement of the functional assignments of the various VCO's is indicated by the flight 70-4 configuration
shown in table IV. The signal on the 165 kHz VCO was the asynchronous pulsed-code-modulation (PCM) output of the pulse height analyzer. Also shown in table IV is the format of the two data commutators which were used on all flights for the transmission of housekeeping data which were not required on a full time basis. Each commutator was transmitted on a separate VCO, and the uses of the other VCO's are indicated in the table.

At the ground station, which is represented schematically in figure 8, additional information is recorded along with the telemetered data. The addition of the frequency standards for the last two flights meant that more of the data could be used in temporal analyses. With only WWV as a time reference on the first two flights, ten minutes in every hour of data were lost due to the absence of recognizable "ticks" in the WWV broadcast (see section V). With the implementation of the GS IV system, the real-time work load on the ground controllers was considerably increased. The addition of a data channel which recorded the sounds occurring in the control room lessened the controllers burden of documenting the events which transpired during the flight. For instance, all commands were made audible on the voice
TABLE IV

GS IV-B
COMMUTATOR FORMATS

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 GRND</td>
<td>1 -2.47 V REF.</td>
</tr>
<tr>
<td>2 +4.81 V REF.</td>
<td>2 GRND</td>
</tr>
<tr>
<td>3 SLOW HA POT</td>
<td>3 +2.31 V REF.</td>
</tr>
<tr>
<td>4 FAST HA POT</td>
<td>4 ⊥ MAG</td>
</tr>
<tr>
<td>5 SLOW DEC POT</td>
<td>5 ⊥ MAG</td>
</tr>
<tr>
<td>6 FAST DEC POT</td>
<td>6 P.SW. -1</td>
</tr>
<tr>
<td>7 A RATERMETER</td>
<td>7 P.SW. -2</td>
</tr>
<tr>
<td>8 B RATERMETER</td>
<td>8 NS LEVEL</td>
</tr>
<tr>
<td>9 ALTIMETER</td>
<td>9 EW LEVEL</td>
</tr>
<tr>
<td>10 MAIN AMPS</td>
<td>10 COMMAND RECEIVER STATUS</td>
</tr>
<tr>
<td>11 MAIN VOLTS</td>
<td>11 REJECT RATE</td>
</tr>
<tr>
<td>12 H V M A GUARD</td>
<td>12 + 12 V PSM</td>
</tr>
<tr>
<td>13 H V M B GUARD</td>
<td>13 - 12 V PSM</td>
</tr>
<tr>
<td>14 HVM PLASTIC</td>
<td>14 ⊥ MAG</td>
</tr>
<tr>
<td>15 THERMISTOR</td>
<td>15 ⊥ MAG</td>
</tr>
<tr>
<td>16 TM/60 HZ.</td>
<td>16 BOX THERMOSTATS</td>
</tr>
<tr>
<td>17 HEATER AMPS</td>
<td>17 THERMOSTATS (FRONT)</td>
</tr>
<tr>
<td>18 HEATER VOLTS</td>
<td>18 THERMOSTATS (REAR)</td>
</tr>
<tr>
<td>19 + 28 v REG MONITOR</td>
<td>19 THERMOSTATS (END CANS)</td>
</tr>
<tr>
<td>20 + 5 v REG MONITOR</td>
<td>20 MOTOR THERMOSTATS</td>
</tr>
</tbody>
</table>

RA MODE PERIODS
(milliseconds)

<table>
<thead>
<tr>
<th>MODE</th>
<th>EAST</th>
<th>WEST</th>
<th>DRIFT SPEED</th>
<th>OSCILLATOR FREQS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>158.4</td>
<td>184.2</td>
<td>-643</td>
<td>EAST 630.97 Hz</td>
</tr>
<tr>
<td>2</td>
<td>316.9</td>
<td>368.5</td>
<td>+123</td>
<td>WEST 542.64 Hz</td>
</tr>
<tr>
<td>3</td>
<td>310.6</td>
<td>361.1</td>
<td>+107</td>
<td>FAST</td>
</tr>
<tr>
<td>4</td>
<td>304.2</td>
<td>353.8</td>
<td>+ 91</td>
<td>REVERSE 250.0 Hz</td>
</tr>
<tr>
<td>5</td>
<td>297.9</td>
<td>346.4</td>
<td>+ 74</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>291.6</td>
<td>339.0</td>
<td>+ 56</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>285.2</td>
<td>331.7</td>
<td>+ 38</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>278.9</td>
<td>324.3</td>
<td>+ 18</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>272.5</td>
<td>316.9</td>
<td>- 2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>STOP</td>
<td>STOP</td>
<td>+888</td>
<td></td>
</tr>
</tbody>
</table>

FAST REVERSE PERIOD: 8.000 ms

VCO ASSIGNMENTS

<table>
<thead>
<tr>
<th>VCO</th>
<th>RANGE</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.9</td>
<td>0-5v</td>
<td>TM CURRENT - 60 Hz COMMANDS</td>
</tr>
<tr>
<td>5.4</td>
<td>0-5v</td>
<td>PARALLEL MAG</td>
</tr>
<tr>
<td>7.35</td>
<td>+2.5v</td>
<td>COMMUTATOR B</td>
</tr>
<tr>
<td>10.5</td>
<td>+2.5v</td>
<td>COMMUTATOR A</td>
</tr>
<tr>
<td>14.5</td>
<td>-5v</td>
<td>RA PULSES</td>
</tr>
<tr>
<td>22.0</td>
<td>-5v</td>
<td>REJECT RATE</td>
</tr>
<tr>
<td>30.0</td>
<td>+2.5v</td>
<td>PCM</td>
</tr>
<tr>
<td>165.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 8
(see page 47)

This schematic diagram of the RUG-RAG ground station shows the arrangement of electronic equipment used to receive telemetry and record data during balloon flights.
FIGURE 8
RUG-RAG GROUND STATION RECEIVING/RECORDING SYSTEM

NOTES
1. FLIGHT 70-4 ONLY
2. 10 KHZ OSC SUBSTITUTED ON FLIGHT 69-1
channel by placing a walkie-talkie next to one of the microphone pick ups. The voice channel was particularly useful in interpreting those portions of the flight when the telescope was being moved from one object to another.

A wealth of data is recorded during each flight, yet only a small part of it is of direct scientific value: (1) the gamma-ray counting rate, (2) timing information, (3) telescope pointing direction, and (4) balloon altitude. The PCM has already been discussed, and timing considerations will be treated in the next section. Telescope pointing is determined from data on commutator A (hour angle, and declination values), from balloon tracking data and from ephemeris calculations. (The two earlier flights did not have the hour angle data; hour angles were calculated from the known rotation rate of the right ascension motor and an initial value measured on the ground.) Altitude data (also transmitted on commutator A) are obtained from a thermal-conductivity-sensing pressure transducer and are used to correct measured fluxes for the effects of atmospheric absorption.
V. DATA ANALYSIS

After the completion of a successful balloon flight, the information obtained during the observation resides on a series of analog magnetic tape reels. The data of direct scientific interest is contained on the PCM channel (the energy of each detected X-ray event) and on the timing channels. For the determination of time-averaged X-ray fluxes, only the PCM channel is needed since tape playback provides a time basis of sufficient accuracy for this purpose. For detailed temporal analyses, however, the timing channels are of the utmost importance. The first task in the reduction analysis, therefore, is to retrieve the PCM and timing data and convert them into a readily usable form.

A. Analog to Digital Conversion

The types of analysis described herein would not have been possible without the use of digital computers. The Rice University machines which have been used in the analyses are therefore described briefly in appendix A.

The task of data manipulation may be visualized as follows. Due to the relatively low X-ray counting rates involved (i.e., the counting rate is much slower than the PCM telemetry bit rate), the raw data may be considered as a sequence of discrete events rather than a sequence of measurements of a
continuous counting rate. The data tapes, if unwound and laid out in a linear fashion would constitute a time coordinate axis. At various points along this axis exist delta functions (of the Dirac type) which indicate the occurrence of an X-ray count. Each delta function has associated with it a channel number which tells how much energy was deposited in that event. The data reduction process, then, consists ofcataloging each delta function as to the precise time of occurrence and the value of its corresponding channel number. Since typical observation times and counting rates are \( \sim 5 \) hours and 20 per second respectively, the catalogue which results from the analysis can have more than 100,000 entries. Hence the need for computer-assisted analyses.

The otherwise straightforward process of reading the data tapes and cataloging the times and channel numbers is somewhat complicated by two effects: (1) inappropriate format of the timing information and (2) anomalies in the data. The ultimate time base used for all four flights was that provided by the broadcasts of radio stations WWV and WWVH which are operated by the National Bureau of Standards. These broadcasts\(^1\) are quite easily capable of providing the 1 milli-

\(^1\) The broadcast stability is better than one part in \( 10^{10} \), but propagation through the atmosphere significantly degrades this accuracy.
second time resolution used for the data analysis, but an interpolation scheme is needed since the broadcasts carry time "ticks" only every 1000 milliseconds, i.e., at one second intervals. As described below, the interpolation procedure can be more or less difficult depending upon how much foresight has been exercised.

Data anomalies seem to be inevitable and stem from several causes: telemetry noise, instrumental malfunctions (either in ground equipment or in flight hardware), ground controller errors, and computer malfunctions. Though programs have been written which can handle many of these situations, some require direct, manual intervention in order to interpret and circumvent the problem in the most reasonable fashion.

Figure 9 shows schematically the instrumentation used to accomplish the data reduction task. The transfer of the PCM words from the analog to the digital flight tapes is a relatively simple matter since the PCM word is already in a digital format. During the data tape playback, the SDS-92 simulates the Nuclear Data Multichannel Analyzer (MCA) while at the same time monitoring the overall process. After each tape reel has been played back, the results of the SDS simulation are compared with the MCA output to assure the proper operation of the system. (The MCA accumulates the number of
FIGURE 9
(see page 53)

Block diagram illustrating the use of computers and peripheral electronic equipment for the task of data reduction.
occurrences of each channel number and outputs a count total for each of the 128 channels.)

As each channel number is brought into the SDS memory and placed into the output buffer, it must also be assigned a time value. The computer obtains this value by reading the clock register which is maintained by the Astrod Data Time Code Translator (TCT). The TCT updates the time of day (contained in the clock register) every millisecond, as determined from the time code signal it receives as input. This input comes either from the tape recorder or directly from the Astrod Data Time Code Generator (TCG). The TCG may be operated either on an internal time base (specifications claim a stability of 1 part in $10^8$ for the internal crystal oscillator) or on an external frequency. Table V indicates the various timing modes used for the individual flights. When the TCT is not linked to a frequency standard recorded in real time, the clock times provided by the TCT can only be used as an interpolation scheme between the WWV ticks. These ticks were relied upon exclusively for absolute timing for flights 66-1 and 67-1. The fact that, for these flights, the tape recorder played back the tapes at a speed differing significantly from the real-time rate was primarily due to the use of several different tape recorders. The X-ray times
TABLE V

TIMING METHODS

<table>
<thead>
<tr>
<th>FLIGHT</th>
<th>SOURCE OF INPUT TO TIME CODE TRANSLATOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>66-1</td>
<td>TCG operated on internal time base during data playback (interpolation between WWV ticks)</td>
</tr>
<tr>
<td>67-1</td>
<td>same as for flight 66-1</td>
</tr>
<tr>
<td>69-1</td>
<td>TCG operated on external 100 kHz signal from signal conditioner which was used to multiply by 10 the 10 kHz frequency recorded in real time during the flight (conditioner also extrapolated across any gaps occurring in the input signal)</td>
</tr>
<tr>
<td>70-4</td>
<td>time code channel of data tapes; time code recorded in real time (during flight) from TCG operated on internal time base and synched to WWV</td>
</tr>
</tbody>
</table>
were brought into synchronism with WWV time by a program called TSHIFT later in the analysis on the B5500 computer.

It should be noted that the use of WWV alone as a time base results in a degradation of the timing resolution. The interpolation procedure assumes discrepancies from a linear time rate are due to tape playback effects. In reality, the WWV propagation time from Ft. Collins, Colorado, to Palestine, Texas, has a "scatter" of about ± ½ millisecond and this effect contributes significantly to the non-linearity of the time base. Furthermore, since 10 minutes of each hour of the WWV broadcast lack the time "ticks", not all data can be used (portions obtained when no WWV "tick" is present have been discarded).

When an accurate reference frequency is recorded in real time, these problems are eliminated. Even though the WWV propagation "scatter" from Hawaii or Colorado to Argentina may be as large as ± 4 ms., the time resolution was maintained at ± 1 ms. because WWV was only used as a check on the TCG's performance. In evaluating the TCG's time base, the mean of many WWV arrival times has been used; and the "scatter" has therefore been removed.

The SDS processes an X-ray event each time the I5 interrupt (see figure 9) is triggered by the PCM decoder and
processes a WWV tick each time the I6 interrupt is triggered by the tick recognizer. A WWV tick requires only that the clock be read and the time entered in the output buffer; while, as mentioned above, an X-ray event also requires the transfer of the channel number. The use of the auxiliary interrupt I7 provides a convenient means of timing other events, such as the occurrence of noisy PCM. For an I7 interrupt the SDS merely records the time on the clock. An identifying code is included with each time to distinguish the various types of interrupts.

When the in-core data buffer is filled, the SDS dumps it to digital magnetic tape; and that tape record essentially becomes the catalogue of X-ray events. However, further manipulation is required to put the catalogue into a form more useful for extensive analysis.

Due to programming considerations, the remainder of the analysis was carried out on the B5500 computer. Figure 10 is a flowchart of the data manipulation process used for flights 66-1 and 67-1. When the procedures were originally developed the programs were written to include a great deal of programmer intervention, since it was not really known, a priori, what "good" data should look like. As experience was gained and a better understanding of the data developed,
FIGURE 10
(see page 59)

Flow chart indicating the computer processing required in order to examine the X-ray data for periodic pulsations. The amount of data manipulation varied, depending upon the timing method employed during data acquisition; as did the degree of programmer intervention required to ensure the proper functioning of the computer programs.
the programs were made "smarter" and could run in a more automated fashion. Also, the instigation of real-time time-base recording greatly simplified the data manipulation task. For the two earliest flights, processing through TSHIFT was required to synchronize the catalogued times accurately to WWV and to weed out the anomalies in the X-ray data. For the last two flights, however, some analyses could be performed directly on the CONVRT tapes, and the need for the programs TCLEAN and TSHIFT was eliminated since the XCLEAN tape times were already synchronized. Also the instructions input to XCLEAN for these flights were essentially segmentation information rather than detailed correction criteria.

B. Determination of Time-averaged Flux

The flux-determination method used by RUG-RAG has been described previously and in great detail (see, e.g., Fishman 1969). More recently, Johnson (1972) has revised and re-implemented computer programs to accomplish the analysis, and his programs were used to determine the time-averaged flux deduced from the Vela observations. For flights 67-1 and 69-1, analyses of this type were carried out shortly after the flights and have been reported in the literature (Haymes et al., 1968a; Haymes and Harnden, 1970). It was
not possible to derive such a flux from the data of flight 66-1 since no observations of the background counting rate were made.

The difficulties (mentioned in section IV-C) of making background measurements not withstanding, the time-averaged residual method (TAR) is a fairly sensitive technique. It not only allows long exposure times to the candidate source object, but also provides accurate background measurements which are usually free from the effects of time variations. The TAR method essentially determines the difference between two counting rates, the total rate $T$, and the background rate $B$. If the observed object is indeed a gamma-ray source emitting at a rate $S$, then the three rates are related by $T = B + S$, and $S$ may be found as the difference between $T$ and $B$. If these two rates are measured using equal exposure times, $t$, and if the usual counting statistics are assumed to apply, then the standard deviation ($\sigma$) or uncertainty in the net rate is given by: $\sigma_S = \sqrt{(T + B)t^{-\frac{1}{2}}} = \sqrt{(S + 2B)t^{-\frac{1}{2}}}$. A measure of the sensitivity is afforded by the ratio (often called chi) of the excess rate to its associated sigma: $\chi = \frac{S}{\sigma_S} = S\sqrt{\frac{t}{S + 2B}}$. $\chi$ has been expressed in terms of $S$ instead of $T$ because this expression is useful in making an order of magnitude estimate of the sensitivity obtainable.
for a proposed experiment. The approximate source strength can be anticipated and used in this expression to determine what exposure time would be required to make a statistically significant observation.

The details of the TAR method will not be described here. However, one peculiarity of the flight 70-4 Vela data analysis should be pointed out. Since the primary goal of the Vela observation was the detection of PSR 0833, only thirty-minutes out of the five hour period were spent in measuring the background. The result for the TAR analysis is that nothing is gained by using more than an equivalent thirty minutes of source observations. Though the uncertainties in the total rate $T$ could be reduced by a factor of $\sim 3$ by using all the data, the error associated with $S$ would not decrease appreciably since it depends upon $\sqrt{T + B}$. Furthermore, one advantage of the TAR technique is that it compares only measurements which are contiguous in time and of comparable length. Hence the source observations used in the TAR analysis were restricted to ten-minute intervals on either side of each background segment. In the analysis, the source segments on both sides of a background segment were used to form an average rate from which the background rate was subtracted. This differs from the usual procedure which averages the
background rates on either side of a source observation, but conceptually the two methods are equally valid. A difficulty does arise, however, when corrections for atmospheric absorption are applied to the net rate. Mean correction factors are used in either case, but when source segments are averaged instead of the background segments, the data segments which contributed to the net rate are further removed from the mean time used to calculate the correction factor. (The time dependence of the factor is due to changes in the atmospheric path length which, of course, depends upon the zenith angle.) It turns out, however, that this is a small effect (less than 10%) and can be safely neglected.

C. Short-Term Fluctuations

The ability to detect short-term fluctuations in a counting rate depends upon the intensity of the flux which is being observed. For situations which are limited by counting statistics, any variations in a rate $R$ must be larger than the standard deviation, $\sigma_R$, in order to be detectable. The relative uncertainty, $\delta$, may be defined as $\delta = \frac{\sigma_R}{R}$, and expressed in terms of the observing time $t$ as: $\delta = (Rt)^{1/2}$. Relative changes in the count rate must be three or four standard deviations to be believable, hence the restriction on the observable percentage change $X$ is: $X \gtrsim 400 \delta$. For a
known counting rate, the detectable changes can easily be calculated from this simple relation. For a count rate of 10 per second, for instance, two-, five-, and ten-minute observation periods will reveal variations of 12, 7, and 5 per cent, respectively, at the four standard deviation level. A useful intuitive feeling for the statistics of such an experiment is obtained by answering a question like: how long an observation is required to reduce sigma to one per cent? The answer, obtained from $\delta$ as given above, is $10^3$ seconds or about 17 minutes.

It is fairly obvious from the above discussion that breaking an observation into a number of short intervals is not a very sensitive way to examine temporal behavior. It is sometimes adequate, nonetheless, and just such an analysis is described in section VI-D. A program called SEGMENT/CONV691 was used to prepare two-minute and ten-minute observation intervals from the CONVRT output tape for flight 69-1. The normalized counting rate in selected energy ranges was then plotted as a function of time and examined visually for significant deviations. The results of this analysis are reported in section VI.
D. Temporal Analysis

It seems generally true that the more information that is to be extracted from a given set of data, the more effort that must be expended in the analysis. While the periodogram (a plot of power-spectral density versus frequency or period) obtained from a Fourier analysis contains a great deal of information regarding the time characteristics of the data, such a calculation, for large data records, can be prohibitively expensive. Quite apart from the matter of cost is the question of the quality of the data. Data limited by the poor statistics inherent with low signal to noise ratios may not be capable of yielding the desired information no matter how much computational effort is expended.

With the discovery of the pulsar phenomenon, such temporal analysis has become almost a routine procedure for many astronomers, particularly those doing experiments at radio frequencies. Soft X-ray astronomers, too, make frequent use of such analyses, but their rocket data are fairly well suited to this approach since fluxes are relatively high and observation times relatively short, in comparison with balloon data obtained at hard X-ray wave lengths. A comparison of the original X-ray pulsar discovery by the Naval
Research Laboratory (NRL; Fritz et al. 1969) with the early RUG-RAG detection of NP 0532 (Fishman, Harnden and Haymes 1969a) will illustrate the point to be made here. NRL had about 40 seconds of data, used a sampling interval of 1.6 milliseconds and computed a periodogram with a frequency resolution of about 0.5 hz. Assuming for the sake of comparison that the RUG-RAG data were "equally as good" (i.e., capable of producing a similar periodogram), then the power spectrum analysis of the 80 minutes of hard X-ray data would take approximately 120 times as much effort since the calculations would have to be carried out with that many more values of the sampled function (i.e., counting rate). A factor of ten in computing time can remove something from the realm of feasibility; 120 would surely be a prohibitive factor. In fact, the two sets of data are probably not "equally as good"; but rather, the NRL data is better due to the higher signal to noise ratio obtainable in rocket experiments. This latter conclusion is reached from a comparison of the pulse profiles obtained by the two groups; the soft X-ray profile (see figure 2 of Fritz et al. [1969]) is of greater statistical significance than the hard X-ray one (see figure 1 of Fishman, Harnden, and Haymes [1969a]). The two profiles were created using essentially the same technique. Arguments of this type
have led to the use of a different technique with hard X-ray data.

1. The Superposed Epoch Method

Periodic phenomena in which strict phase-coherence is maintained from one cycle to the next may be studied with a very high level of sensitivity by the use of a superposed epoch technique, provided that the period of the phenomenon is known with sufficient accuracy. In such an analysis the values of some function \( f \) of time (e.g., X-ray counting rate) are superimposed upon themselves with a "folding length" or epoch of \( P \). Hence the superposed epoch function, \( SE(t) \), is calculated from the function \( f(t) \) as:

\[
SE(t) = f(t) + f(t + P) + f(t + 2P) + f(t + 3P) + \ldots
\]

In data analyses, the time coordinate is usually taken as discrete, so that \( t \) is replaced with \( t_i \), such that: \( t_i = i\Delta t \), where \( \Delta t \) is some basic resolution time or sampling interval. The function \( SE(t) \), which is defined only on the time interval, \( 0 \leq t_i \leq P \), then becomes:

\[
SE(t_i) = \sum_{n=0}^{N} f(t_i + nP).
\]

The nature of pulsar radiations is particularly well suited to this type of analysis. The function of time is the sum of a "noise" component and the intrinsic pulsar emission. A remarkable property of pulsars is that the time
behavior of the emissions from most of them is very sharp, like a highly peaked Gaussian function. One narrow phase region of each period exhibits considerable enhancement over the remainder of the period. (This is true for single-pulse pulsars; pulsars with double or even more complicated pulse structures have more than a single preferred phase.) As the data from successive periods are folded into the accumulating value of $SE(t_i)$, the portion of the interval, $0 \leq t_i \leq T$, in which the preferred-phase region falls will show the enhancement over the rest of the interval. In such a situation, the time coordinate must be folded with an accuracy great enough that the sharp nature of the pulsar emission is not smeared out. Suppose, for example, that the function $f(t_i)$ differs significantly from its mean value during only one sampling interval of each period. If the function is superposed for some total time $T$, then the requirement that the "pulse" remain within one sampling interval in the resulting function $SE(t_i)$ means that $P$ must be known to an uncertainty $\Delta P$ of: $\frac{\Delta P}{P} \leq \frac{\Delta t}{T}$

This relation is derived from the notion that an infinitely sharp function of time with a true period $P$ will drift from one edge of the sampling interval to the other if the period used to fold the time base of total length $T$ is in error by $\Delta P$. In practice, it is the pulsar's pulse width, $\Delta t$, ...
which should be used in the above relation: \( \frac{\Delta P}{P} \leq \frac{w \Delta t}{T} \)

As an application of this expression, consider the Vela pulsar which has a period of \( P \approx 0.089 \) seconds and a pulse width of \( w \Delta t \approx 0.003 \) seconds. If phase coherence is to be maintained over a \( T = 5 \) hour observation, then \( \Delta P \) must be about 15 nanoseconds.

2. Implementation of the Method

The data catalogue whose preparation was described in part A of this section is particularly well suited to a superposed epoch analysis. If the resolution time of one millisecond is considered as a sampling interval, then it is evident that a majority of such samples of the gamma-ray counting rate result in a value of zero, since the counting rate is only about 20 per 1000 milliseconds. This sparseness of the data could present a problem in some types of analysis, but it is actually an advantage in a superposed epoch method. With this method, the calculational effort required is determined by the total number of catalogue entries rather than the time interval spanned by the entries.

Since most of the data have been segmented in time by the observational technique, the problem of determining the phase of each X-ray count splits into two parts: (1) that of determining the phase of each count relative to the other counts
within the same segment (typically about ten minutes long),
and (2) that of determining the phase of each data segment
relative to the other segments so that all segments may be
added coherently.

Consider the first problem. Suppose that 10 minutes of
data are to be superposed using a constant period P. The
catalogued times are measured relative to some point which
is defined as zero (clock times for most flights, when
synchronized to WWV, were relative to zero at midnight Greenwich
Mean Time). If \( t = 0 \) is arbitrarily designated as zero phase,
then the phase of any time \( t \) is determined from a knowledge
of the number of cycles (of period P) which have elapsed
during that time. That number can be represented as an
integer plus a fractional part; and it is the fractional part
that contains the phase information, in units of period.
(The phase can obviously be converted to other units; for
instance, phase in degrees would be obtained by multiplying
the fractional part by: 360 degrees per period.)

The number of cycles elapsed in time \( t \) is determined
simply by dividing \( t \) by \( P \). Just as one can stop when he
has found the largest integer result, leaving the answer
expressed as a whole number plus a remainder, so, with ap-
propriate programming, can a digital computer. The use of
remainder division is usually written in computer language as something like: \( T \mod P \). The result of this operation comes out in the same units used to express \( P \) as a value between zero and \( P \). The extension from this result to the calculation of the superposed epoch function is straightforward. \( SE(t_i) \) is set up as \( n \) accumulators or bins, one for each width, \( \Delta t \), within the period \( P \) (i.e., \( n = \frac{P}{\Delta t} \)). The accumulators are initially all set to zero. Then as each catalogue entry is \( \mod \)-ed with \( P \) and its phase determined (as \( t \mod P = m\Delta t \)), the bin corresponding to the phase of \( t \) (i.e., the \( m \)th one) is incremented. When all X-ray count times within a data segment have been processed, each accumulator of \( SE(t_i) \) contains a number indicating how many X rays occurred in that phase interval. \( SE(t_i) \) is usually plotted as a histogram of number of counts per bin versus phase measured in bins. For pulsar analyses, such histograms are called "pulse profiles". (The term "light curve" is often used for the optical pulsar.)

If the period for which data are to be searched were a constant, the second problem (that of coherently combining data from several different segments) would be a simple matter. This is not the case, however. Both PSR 0531 and PSR 0833 exhibit a significant and well defined lengthening
of period with time. The magnitudes of this effect are \( \sim 36 \) and \( \sim 10 \) nanoseconds per day, respectively. In addition to this intrinsic change, an even greater effect is caused by relative changes in the Doppler shift due to the motion of the observer (i.e., the balloon-borne telescope). As a result of these changes in period, the task of adding segments together while still preserving the sharp features of \( SE(t_i) \) depends rather sensitively upon an accurate knowledge of the period variation.

3. Period Variations - The Doppler Effect

As indicated above, the intrinsic period slowdown must be included in the analysis of the temporal behavior of the period, but the information given in table VI shows the intrinsic change to be much smaller than that caused by a varying Doppler shift. The relativistically correct expression for the Doppler shifted period \( P \) in terms of the "true" period \( P_0 \) is:

\[
P = P_0 \frac{\sqrt{1 - \beta^2}}{1 - \beta},
\]

where \( \beta \) is the ratio of the observer's velocity \( v \) (positive away from the source) to the speed of light. The numerator contains the relativistic "time dilation" effect, while the denominator is the classical result. In writing \( P = P_0 (1 + \beta) \), one is ignoring terms of order \( \beta^2 \) and higher which arise both from relativistic effects and from the binomial expansion of the denominator. The effect of the
<table>
<thead>
<tr>
<th>FLIGHT</th>
<th>OBSERVED PULSAR</th>
<th>P (SEC)</th>
<th>ΔP (INTRINSIC)*</th>
<th>ΔP (APPARENT)*</th>
<th>ΔP (TOTAL)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>66-1</td>
<td>PSR 0531</td>
<td>0.033</td>
<td>3.5</td>
<td>14.5</td>
<td>18.0</td>
</tr>
<tr>
<td>67-1</td>
<td>PSR 0531</td>
<td>0.033</td>
<td>9.2</td>
<td>36.7</td>
<td>45.9</td>
</tr>
<tr>
<td>69-1</td>
<td>CYG X-1</td>
<td>0.073</td>
<td>unknown</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td>(pulsar)?</td>
<td>(?)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70-4</td>
<td>PSR 0833</td>
<td>0.089</td>
<td>2.0</td>
<td>91.0</td>
<td>93.0</td>
</tr>
</tbody>
</table>

*ΔP represents the difference between the value of P at the beginning and that at the end of each observation. Units for ΔP are nanoseconds.
$\beta^2$-order term is always to lengthen the period (regardless of the sign of the velocity) while the classical effect shortens or lengthens the period according as $v$ is toward or away from the source. For the case of $v$ equal to the earth's orbital velocity, $\beta^2$ is about $10^{-8}$, so the change in a period of 89 milliseconds is just under one nanosecond. Effects of this size and smaller have been neglected in the present analysis. For the classical Doppler effect, it is the velocity component along the line of sight to the observed object that is to be used in the formula.

Pulsar observations are generally referred either to the heliocenter or to the barycenter (center of mass of the entire solar system). The distinction between the barycenter and the center of the sun is a rather fine one; the barycenter may be said to "orbit" about the sun at a distance of about 1½ solar radii with a "period" on the order of Jupiter's eleven-year sidereal period. The magnitude of this velocity is about 13 meters per second, which is quite small compared to the earth's orbital speed of about 30 kilometers per second. The calculation of an observer's heliocentric velocity, while vastly simpler than a calculation of his motion relative to the barycenter, is still a non-trivial task.

The computer program (Ball 1969) used to calculate helio-
centric velocities for the balloon flights takes into account the following motions, which are listed in the order of decreasing relative magnitude: (1) center of mass of the earth-moon system about the sun (2) the observer about the center of the earth, and (3) the earth about the center of mass of the earth-moon system. The mean velocities involved in these three motions are roughly 30, 0.5, and 0.01 km sec$^{-1}$ respectively. Since it is only the radial velocity component which enters into the Doppler shift expression, it is very important to use precise celestial positions in the velocity calculation. The fact that this was not realized early enough by RUG-RAG necessitated the publishing of an Erratum (Fishman, et al. 1970) to correct an error of 13 nanoseconds. This error stemmed entirely from a failure to use the precessed coordinates of PSR 0531 in the calculation. In the 17 years from 1950 to the 67-1 flight, the south-preceeding central double star of the Crab Nebula had moved $\omega \frac{1}{2}$ degree in apparent position; and that small difference changed the radial velocity by nearly $2\frac{1}{2}$ per cent.

The Doppler shift program was used to calculate the period change at many different times during the course of the pulsar observations. The data from each flight were broken into time segments of no longer than 20 minutes. Within each
segment, a constant period was used; but each segment had a different constant period as determined from the Doppler program. This technique essentially reduces to the approximation of a curve (nearly parabolic) by many short, straight-line segments. The phase (relative to \( t = 0 \)) at the starting time of each segment is determined by a type of numerical integration and is stored for later use in the superposed epoch search. A two-dimensional vector (called SHIFT) is required to store the information since the phase correction is a function not only of time, but also of the magnitude of the period \( P_0 \). It is because the data are usually searched for many different values of \( P_0 \) during each program run that SHIFT must be calculated for the period dimension. Though the values contained in SHIFT vary with the absolute period, the same relative Doppler shifts are used to calculate each set of SHIFT values.

As the superposed epoch method is applied to determine the relative (to the starting time of the segment) phase of each X-ray event that occurred within a given segment, the appropriate value of SHIFT is added to the phase in order to map it to the phase relative to \( t = 0 \). In this manner, data from all segments are combined coherently.

The ability to maintain phase coherence over long time
intervals is essential to observations at hard X-ray energies where the signal to noise ratio is so low. The use of long observation times necessitates a very accurate knowledge of the period which is sought, and this means that very small effects (like minute changes in the observer's velocity) can be important. The various versions of the superposed epoch program contain the accurate period information in the \text{SHIFT} vector which is really the essence of the entire analysis.

4. Useful Searching Techniques

When the pulsation period for which data are to be examined is only known approximately, the superposed epoch method can only be applied by guessing values for the period. In order to avoid missing the pulsation by skipping past the true period, the period guesses must be spaced very close together - on the order, \( \Delta P \sim \frac{\Delta t}{T} \) P, as derived earlier in this section. It can readily be seen that a large number of searches may be required to locate the sought pulsations.

The result of searching the data at a given period is the superposed epoch function \( \text{SE}(t_i) \) which can be plotted as a pulse profile. In dealing with large numbers of such profiles, it is helpful to condense the information contained in each one to a single number. This single number can then be scanned, as the period is varied, for evidence of pulsations.
This not only makes the scanning task easier but also lessens the chance that a significant feature will be overlooked.

Two such single-number indications have been used, in the investigations described here, and are discussed more fully in appendix B. The first is simply the greatest deviation of \( SE(t_1) \) from its mean value, i.e., the greatest number of counts in a single bin minus the mean number per bin. This deviation is expressed in terms of the standard deviation associated with the bin count (defined as the square root of the number of counts in the bin) and, for convenience, is called MAXCHI. For the large number of counts normally registered, the applicable statistical rules (Poisson) become nearly Gaussian and deviations of individual bins from the mean follow a normal (or Gaussian) probability distribution. The deviation expressed in units of sigma is usually called \( \chi \) (hence the name, MAXCHI), and its value gives a direct indication of the likelihood that such a deviation is due to random chance. For instance, the probability that \( \chi > 3.0 \) by mere chance is about \( 10^{-3} \), whereas a value of \( \chi > 4.1 \) has only a 1 in \( 10^5 \) chance of being a statistical fluke.

The other number used is the chi-square sum of a fit of the pulse profile to a flat curve with the mean value.
This parameter gives a measure of the entire profile whereas MAXCHI characterizes only a single bin.

For a pulsar with a simple, single-pulse time behavior, the MAXCHI was found to be a more sensitive indicator. When the duty cycle is only a few per cent, the profile does not deviate very much from the mean (assuming a weak pulsar signal superimposed on a relatively large background level). On the other hand, when the duty cycle reaches \( \frac{1}{4} \) or \( \frac{1}{2} \), the profile is quite different from a straight line. In this case, while any individual bin may not be more than 3 or 4 sigma from the mean, the chi-square sum can be very significantly different from the value expected from a flat profile. Hence the chi-square sum is a more sensitive indicator in this case.

If the pulse profile of the particular pulsar is known beforehand, then an even more sensitive indicator would be the chi-square sum for a fit of the known profile to the \( SE(t_i) \) function. This technique has not been employed in the present analysis, however, since the profiles were not known \textit{a priori}. 
VI. HARD X-RAY MEASUREMENTS

During the balloon flights described in section III, observations at hard X- and gamma-ray wavelengths were conducted for three widely separated regions of the sky. The Crab Nebula, in the constellation of Taurus, was viewed during flights 66-1 and 67-1; the x-ray source CYG X-1 in the constellation of Cygnus was observed during the 1969 flight; and the radio pulsar, PSR 0833-45, in the constellation of Vela was the first object viewed during the 1970 November 25 flight. Significant fluxes of radiation were detected on all of these flights. Reported here, along with some findings which have already been published, are two new pulsar results: evidence is presented for (1) the first detection of PSR 0833-45 at any wavelength other than the radio, and (2) the measurement, nearly a year prior to the previously earliest measurement, of the period of PSR 0531+21.

A. Taurus

Haymes et al. (1968a) reported the first detection of gamma rays from the Crab Nebula; Ellis (1967) discussed this experiment in greater detail. When Fishman, Harnden, and Haymes (1969a) reanalyzed the same data for evidence of pulsations from NP 0532 (PSR 0531+21), they hoped to answer two questions: (1) does the Crab pulsar emit gamma rays? and
(2) at what pulse repetition period (if any at all) did NP 0532 emit in 1967? The second question became all the more important when Radhakrishnan and Manchester (1969) and Reichley and Downs (1969) announced their discovery of the abrupt period change in the Vela pulsar, PSR 0833-45. In a further analysis of the same 1967 data, Fishman et al. (1969b) determined the hard X-ray spectrum of the pulsar.

1. The Period of the Crab Nebula Pulsar

The answer to question (1) was, of course, yes. The final result of the RUG-RAG analysis (Fishman et al. 1970) was a period of $33 \, 071 \, 771 \pm 6$ nanoseconds, measured at the epoch 1967 June 4.597 U.T. This value is in excellent agreement with an extrapolation of the radio data of Richards et al. (1969); the prediction of the extrapolation has an uncertainty of $\pm 2.3$ nsec and lies only 3 nsec below the value actually measured. This agreement seems to rule out a period jump of the Vela type between 1967 June and 1968 November. Although small "glitches" have been observed, in 1969 September and 1971 October (Lohsen, Papaliolios, Carleton, and Horowitz, 1971), in the period behavior of PSR 0531, these are several orders of magnitude smaller than the Vela period-change. Since no such large period-change has yet been observed for PSR 0531, the extension of the time base over which the
pulsar has been observed remains an important task. As demonstrated by Fishman, Harnden and Haymes (1969a) and by Boldt et al. (1969) an effective technique is the re-analysis of old data.

The data from RUG-RAG's flight 66-1 has been reanalyzed, this time for the pulsations of the Crab Nebula pulsar. As mentioned in section IV-B, the lack of background observations during the flight prevented the detection of a signal from the Nebula; but the nature of the pulsar obviates the need for separate background measurements.

In order to determine approximately what the pulsar period would have been at the epoch of the observation, an extrapolation was made from the 1969 radio (Richards et al. 1969) and optical (Duthie and Murdin 1971) pulsar measurements. The formal errors associated with the measured values of $P$, $\frac{dp}{dt}$, and $\frac{d^2p}{dt^2}$ are quite small and lead to a negligible ($\sim 2$ nsec) error when extrapolated to the 1966 data. In view of those authors' comment that systematic errors larger than the formal errors are likely, an estimated uncertainty in the 1966 period of $\pm 5$ nsec seems reasonable. The extrapolated values for the barycentric period of PSR 0531+21 at the epoch 1966 June 12.652 U.T. then become: 33 058 725 $\pm 5$ and 33 058 727 $\pm 5$ nanoseconds, based on the Arecibo and Rochester data,
respectively.

The Doppler correction, as described in section V-D, was computed to be 128 nanoseconds; and since the balloon was travelling away from the pulsar, the predicted apparent period is obtained by adding 128 nsec to the above barycentric periods. Note that a heliocentric correction is applied to a barycentric period; ignoring the distinction between reference frames introduces an error of at most: (velocity of barycenter with respect to sun) X (pulsar period) ÷ (velocity of light) ≈ 1.5 nsec. The predicted apparent period thus becomes 33 058 854 ± 5 nanoseconds.

The X-ray data were searched (using the program CHI/SEARCH) for a range of observed periods about the predicted value. One hundred fifty periods at intervals of 5 nanoseconds (which provided coverage of the period interval from 33 058 465 to 33 059 215 nanoseconds) were scanned using chi-square as the pulse profile indicator. The results of this analysis are shown in figure 11. Although this graph of \( \chi^2 \) versus period is not as impressive as the one obtained from the 1967 data (figure 12), there is a remarkable feature in the vicinity of the predicted period. The width of the feature in the 1966 data (≈60 nsec) is comparable to that exhibited by the 1967 data (≈40 nsec) when allowance is made for the fact that the
FIGURE 11

(see page 85)

Graph of chi-square versus the apparent periods for which the data of flight 66-1 were searched. The crosshatched region indicates the period range predicted by an extrapolation based on 1969 radio and optical data. See the text for further details.
FIGURE 12
(see page 87)

Graph of $\chi^2$ versus apparent period obtained from a superposed epoch analysis of the data from flight 67-1. The crosshatched region indicates the period range predicted by an extrapolation based on 1968 radio data for the Crab Nebula pulsar. Note that the hatched region has been moved from its incorrect position in Fishman et al. (1969b) where this figure appeared originally.
NP0532

45 keV - 200 keV
4 June 1967

$\chi^2$ vs. $X$

Period = 33072000 + X n sec

FIGURE 12
1966 observation spanned a shorter time interval (148 minutes) than did the one in 1967 (190 minute interval). An observed period of $33 \ 058 \ 850 \pm 50$ nanoseconds is deduced for the feature in the 1966 data.

If this evidence is interpreted as a measurement of the PSR 0531 period, then the heliocentric value was $33 \ 058 \ 722 \pm 50$ nanoseconds at the epoch 1966 June 12.652 U.T.

The failure of the chi-square plot to peak sharply is accompanied by pulse profiles which are not of very good statistical precision. There seems to be a double pulse present, possibly with the interpulse enhanced relative to the main pulse, but the profiles are not convincing. It is worth noting that the WWV reception during flight 66-1 was exceptionally poor, hence it is likely that the time resolution of the present analysis was degraded. Such an effect could account for the "low Q" of the chi-square plot and smear out the pulse profiles. An analysis with a time resolution coarser than the width of the feature in the true pulse profile clearly is not capable of extracting the maximum amount of information from the data.

Though the predicted apparent period falls near the center of the chi-square "bump", the large uncertainty in the observed period makes it difficult to draw a definitive
conclusion regarding the success of the extrapolation. One would like to have further information about the period behavior at this early epoch.

RUG-RAG has data, from a balloon flight conducted 1965 October 22, which might permit the detection of NP 0532 since the Crab Nebula was apparently observed (Haymes and Craddock 1966). A re-analysis of this data could lead to a pulsar period measurement, at a still earlier epoch, which would determine whether the pulsar period has really followed the polynomial form that was used for the present extrapolation.

2. The Spectrum of PSR 0531+21

The spectrum of pulsed radiation from the Crab Nebula was determined from the analysis of the 1967 data. The pulse profile shown in figure 13 resulted from a superposed epoch scan of all X-ray counts with channel numbers in the range 6 through 36 (corresponding to energies of 55 to 177 keV). For the spectral analysis, five separate profiles were generated by dividing the data according to the following channel number intervals: 5 - 10, 11 - 22, 23 - 40, 41 - 75, and 75 - 127. The counting rate due to the pulsar was determined for each profile, using the phase regions indicated in figure 13; and corrections were applied to convert the rates to the fluxes which have been plotted in figure 14. The instrumental
FIGURE 13
(see page 91)

Pulse profile in the energy range from 55 to 177 keV. The double-pulse structure is evident. Both pulses contain approximately the same number of counts. The phase intervals used for the determination of the pulsed and background fluxes are indicated. The solid line represents the mean background from the Crab-pointing data. The broken line is the mean number of counts observed while the detector was pointed away from the Crab. Error bars shown are ±1 standard deviation.
FIGURE 14
(see page 93)

Spectrum of NP 0532 in the energy range from 1 to 560 keV. Horizontal error bars represent the widths of the energy ranges for the present measurements. Vertical error bars are ± 1 standard deviation and are statistical in nature. The two upper-limit measurements are at the 2-standard-deviation level. The Crab Nebula spectra are shown for comparison purposes.
Figure 14

\[ I(E) = I_0 E^{-\alpha} \]

- CRAB NEBULA (GORENSTEIN et al 1969)
- CRAB NEBULA (HAYMES et al 1968)
- FRITZ et al (1971)

\[ I(E) = 1.3 E^{-12} \]

NPO532 PRESENT MEASUREMENTS
and atmospheric corrections have been detailed by Ellis (1967). Note that the two highest energy intervals are shown as upper limits; the pulse profiles for these two intervals did not reveal an excess in phase regions marked P in figure 13. As can be seen from figure 14, the emission of the pulsar has a power law (of energy) dependence remarkably similar to that of the Nebula.

Due to the poor quality of the pulse profiles obtained from the 1966 data, it was not possible to make a measurement of the pulsed spectrum; neither, as mentioned earlier, could the Nebular spectrum be determined.

B. Time-Averaged Flux from the Vela Region

A determination of the steady X-ray emission from the observed region in Vela is limited by the short time spent measuring the flux of background radiation. Only ~33 minutes were devoted to background measurements so that exposure to the pulsar would be maximized. Figure 26, which shows the "time line" for the Vela portion of flight 70-4, indicates that pointing segments V2, V4 and V6 were background mode. Also shown in the figure is the pressure-altitude (in milli-bars) of the balloon during the Vela observation. Approximately ten minutes of source-mode data before and after each
of the three segments were used to determine the (20-minute average) source counting rate at the times of the background observations. Hence a total of \( \sim 60 \) minutes of source and \( \sim 33 \) minutes of background data were analyzed in the fashion described in section V-B.

The results of the analysis are presented in figure 15 which shows the excess (above background) counting rate versus channel number and energy. Individual channels have been added together to improve the statistics, and the resulting channel sums, corrected for atmospheric and instrumental absorption, have been plotted in the figure.

A statistically significant deviation from a net rate of zero is found only for the first channel sum, which spans the energy region from \( \sim 25 \) to \( \sim 80 \) keV (channels three through ten inclusive). This point is five standard deviations above zero. It corresponds to a flux of:

\[
\frac{dN}{dE} = (7.2 \pm 1.4) \times 10^{-4} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ kev}^{-1}
\]

at a channel-midpoint energy of \( \sim 52 \) keV. The exact energy of this measurement is uncertain by about \( \pm 15 \) keV due to the effect of turning off detector A, as mentioned in appendix C.

Though no flux was detected at energies above \( \sim 80 \) keV, upper limits (at the 97.5% confidence level) have been established. Table VII lists these results.
FIGURE 15
(see page 97)

Time-averaged counting rate due to a celestial source in the constellation of Vela. The excess above background is shown and has been corrected for atmospheric and instrumental absorption. The data have been added channel-wise (in groups of 10 or 20 channels) to improve the statistics. Errors shown are ± 1 standard deviation.
TABLE VII

UPPER LIMITS TO THE TIME-AVERAGED FLUX
FROM THE VELA REGION

<table>
<thead>
<tr>
<th>Channel Midpoint</th>
<th>Flux Density $(\text{keV cm}^{-2}\text{sec}^{-1}\text{keV}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (keV)</td>
<td></td>
</tr>
<tr>
<td>117</td>
<td>$6.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>190</td>
<td>$5.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>263</td>
<td>$5.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>372</td>
<td>$7.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>517</td>
<td>$7.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>662</td>
<td>$7.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>833</td>
<td>$7.9 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Note: These upper limits (at the two standard deviation level) are based upon ~33 minutes of background data and ~60 minutes of source data.
C. Pulsed X Radiation from Vela

Only those X-ray events which had channel numbers of three through ten were used in the temporal analysis, since it was this energy interval which revealed an excess time-averaged flux from the Vela region. The counting rate in this interval was \( \sim 2.7 \text{ sec}^{-1} \), which means about \( 4 \times 10^4 \) counts were used in computing the superposed epoch functions.

The pulse profile obtained for an observed period of 89 211 275 nanoseconds is shown in figure 16. Bins 12, 13, and 14 are 1.9, 4.1, and 2.2 standard deviations, respectively, above the mean, which is also indicated. Combining these three bins, into a single bin of three times the width, results in a deviation of this triple-bin, from the mean number per triple-bin, of \( \sim 4.8 \) standard deviations. The probability that this feature is due to random chance is quite remote. In fact, even the 4.1-\( \sigma \) bin by itself is rather unlikely. Appendix B gives a discussion of the application of statistics to estimate the likelihood of such deviations from the mean value.

Figure 17 suggests an interpretation for this effect. Shown arbitrarily aligned in phase are the radio pulse obtained by Radhakrishnan et al. (1969) from PSR 0833 and the feature from figure 16. The widths of the two features are
Superposed epoch function, or pulse profile, obtained from an analysis of channels 3 through 10 of the Vela X-ray data. The observed period is indicated. Attention is called to the feature in bins 12, 13, and 14. Each bin represents a phase interval of $\frac{1}{89}$ of the total period (1 bin $\approx$ 1.002 ms.). The solid line indicates the mean count rate while the Vela region was in the detector field of view. The contribution due to the background (i.e., the rate while the detector was pointed away from Vela) is shown with the dashed line.
FIGURE 17
(see page 103)

Partial pulse profile for the Vela radio pulsar shown with the pulse observed in the X-ray data. The features have been arbitrarily phase-aligned to coincide in bin 4. Only part of the total period $P$ has been shown, since the remainder of both the X-ray and radio profiles shows no significant deviations from the mean.
Figure 17

X-RAY PULSE
(40 keV)

RADIO PULSE
(1720 MHz)
RADHAKRISHNAN et al.
(1969)

COUNTS PER BIN

INTENSITY
(ARB. UNITS)

PHASE (BINS, 1 BIN = 1.002 ms)

~ $\frac{1}{10} P$
TABLE VIII

THE PERIOD OF PSR 0833-45
DURING FLIGHT 70-4

BARYCENTRIC PERIOD MODEL*

\[ P(t-t_0) = P_0 + \dot{P}_0(t-t_0) + \frac{\ddot{P}_0}{2} (t-t_0)^2 + \ldots \]

where \( t_0 = 08^h00^m \) U.T., 28 Jan. 1970

\( t-t_0 \) = seconds

\[ P_0 = 0.089212641287 \text{ sec.} \pm 6 \text{ picosec.} \]

\[ \dot{P}_0 = (1.24504 \pm 0.00002) \times 10^{-13} \text{ sec/sec} \]

\[ \ddot{P}_0 = (-1.65 \pm 0.02) \times 10^{-23} \text{ sec/sec}^2 \]

\[ \dddot{P}_0 = (2.82 \pm 0.2) \times 10^{-31} \text{ sec/sec}^3 \]

PERIOD AT \( T = 06^h50^m \) U.T., 25 Nov. 1970:

zero order = 0.089 212 641 3 seconds

first order = 0.000 003 237 4

second order = -0.000 000 005 6

third order = 0.000 000 000 8

ad hoc correction* = 0.000 000 005 1

for 25 Nov 1970

\[ 0.0892158739 = \text{Period predicted from model} \]

\[ 0.0892158790 = \text{best estimate of true period at } T \]

Doppler shift of period due to heliocentric motion of balloon toward pulsar

\[ P = -4474 \text{ nsec} \]

Predicted Apparent Period: 89.211405 milliseconds

*Reichley and Downs (1971a)
intriguingly similar.

However, the interpretation of this X-ray feature as the hard X-ray detection of PSR 0833 suffers from the rather troublesome fact that the pulsation period of the radio pulsar differs by \( \sim 155 \) nanoseconds from the period observed in the X-ray data. Table VIII indicates the method by which the radio period was determined. The uncertainty in the value of 89 211 405 nsec is less than ten picoseconds (10^{-11} \text{ sec}).

The observed period quoted above must be corrected for two effects: (1) drift of the time-code generator's time base relative to WWV, and (2) motion of the balloon relative to the telemetry-receiving station. The time code generator gained about 4 milliseconds on WWV over the five hour observation time; the gain was made in a linear fashion indicating that the frequency standard was in error by a constant amount. A drift of 4 ms in 5 hours implies a correction of \(-20\) nanoseconds for a measured period of \(\sim 89\) milliseconds. During most of the observation, the balloon was moving away from the ground station at a nearly constant rate of \(\sim 33\) knots (\(\sim 60\) kilometers per hour). The effect of this motion is to introduce an additional Doppler correction of \(-5\) nsec. (The effect may alternately be conceptualized as a change in propagation delay due to the increasing balloon to ground station
distance). Hence the period actually observed is 25 nsec less than the value given above, and the discrepancy with the radio period is indeed 155 nsec.

The uncertainty in the observed period is about ± 15 nsec. and can be estimated in two ways. Varying the period used in the superposed epoch analysis by ± 15 nsec "washes out" the 4.1 σ deviation, reducing it to about two sigma. Alternately, the expression for ΔP developed in section V-D may be used to calculate:

$$\Delta P \simeq (3 \text{ ms}) \div (5 \text{ hours}) \times (89 \text{ ms}) \simeq 15 \text{ nsec}.$$ 

Faced with the above facts, one first asks himself whether the analysis leading to the result was done properly. Appendix D is devoted to this question, the answer to which appears to be yes. In fact, one of the more interesting results to come out of the extensive troubleshooting procedures is the following. When a different method of keeping track of the pulsar phase (see appendix D) was substituted for the SHIFT vector described in section V-D, the result was to increase the greatest amount by which a single bin deviated from the mean. This new method has the capability of maintaining phase coherence more accurately than the SHIFT-method. The fact that application of the method produced a MAXCHI of
4.3 indicates that the feature, be it real or be it random chance, has a very narrow width in period-space.

The following conclusion is drawn from the evidence presented here and in appendix D. Either,

(1) The pulsar PSR 0833-45 has been detected at hard X-ray wavelengths and is found to have a period differing from that of the radio pulsations by 1 part in $6 \times 10^5$, or

(2) A highly improbable, purely accidental periodicity exists in the Vela data obtained during flight 70-4; the period associated with these fortuitously precise fluctuations is only 155 nanoseconds shorter than that of the radio pulsar which was in the detector's field of view during the observation.

A choice between these two conclusions cannot be made on the basis of the information presented in this thesis. Yet the weight of evidence in favor of conclusion (1) seems strong enough to justify an exploration of the implications of such a conclusion. This will be done in section VII.

To the best of the author's knowledge, the period discrepancy really does exist. It is not inconceivable, how-
ever, that some effect has been overlooked which would bring the periods into better agreement. The various factors considered in the period determination are discussed in appendix D.

The power contained in the pulse of figure 16 amounts to $6 \pm 2\%$ of the time-averaged flux determined in the preceding section. If this is interpreted as a flux of hard X-rays from the Vela pulsar, then the pulsed X-ray flux, corrected to the top of the atmosphere, is found to be:

\[
pulsed \text{ flux: } \frac{dN}{dE} = (4.3 \pm 1.4) \times 10^{-5} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}
\]

at a channel-midpoint energy of $50 \pm 15$ keV.

Upper limits to the pulsed flux at higher energies have been derived using the same channel-number intervals as plotted in figure 15; the results are tabulated in table IX.

D. Cygnus

The report by Oda et al. (1971) that X-ray pulsations from the object Cyg X-1 had been observed from the UHURU satellite prompted RUG-RAG to perform a reanalysis of the data obtained during flight 69-1. The results obtained in the original analysis (Haymes and Harnden, 1970) indicated that there was a very good chance of detecting the pulsations
TABLE IX

UPPER LIMITS TO THE PULSED X-RAY FLUX
FROM THE VELA REGION

<table>
<thead>
<tr>
<th>Channel Midpoint Frequency (Hz)</th>
<th>Flux Density (W m(^{-2}) Hz(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.83 \times 10^{19}</td>
<td>2.1 \times 10^{-33}</td>
</tr>
<tr>
<td>4.59 \times 10^{19}</td>
<td>1.8 \times 10^{-33}</td>
</tr>
<tr>
<td>6.36 \times 10^{19}</td>
<td>2.0 \times 10^{-33}</td>
</tr>
<tr>
<td>8.99 \times 10^{19}</td>
<td>1.8 \times 10^{-33}</td>
</tr>
<tr>
<td>1.25 \times 10^{20}</td>
<td>2.7 \times 10^{-33}</td>
</tr>
<tr>
<td>1.60 \times 10^{20}</td>
<td>2.9 \times 10^{-33}</td>
</tr>
<tr>
<td>2.01 \times 10^{20}</td>
<td>2.8 \times 10^{-33}</td>
</tr>
</tbody>
</table>

Note: These upper limits (at the 2 standard deviation level) were calculated for an observed pulse repetition period of 89.211275 milliseconds and assume a pulse width of 3 ms. However, they are also valid for a period of 89.211380 ms., which was the apparent period of PSR 0833-45 at the time of the observation (again, a 3 ms. pulse width is assumed).
discovered by the X-ray astronomy satellite.

1. Time-Averaged Flux from CYG X-1

In their 1970 article, Haymes and Harnden reported the measurement of the spectrum of Cygnus X-1 over the energy range from 34 to 567 keV. They found that the data were well approximated by two power laws:

\[
\frac{dN}{dE} = 4.6 \times 10^{-1.91 \pm 0.03} \text{ photons cm}^{-2}\text{sec}^{-1}\text{keV}^{-1}, \text{ for the interval } 34 \text{ keV} < E < 124 \text{ keV, and}
\]

\[
\frac{dN}{dE} = 1400 \times 10^{-3.1 \pm 0.2} \text{ photons cm}^{-2}\text{sec}^{-1}\text{keV}^{-1}, \text{ for the interval } 154 \text{ keV} < E < 449 \text{ keV.}
\]

These spectra were obtained by a least squares method applied to the time-averaged flux determined as outlined in section V.

The published result did not, however, illustrate the excellent nature of the raw data. The region observed (Cyg X-1 and Cyg X-3 were both within the field of view) is the brightest in the "hard X-ray sky". Figure 18 is a graph of counting rate, in three different energy intervals, versus time; the square-wave appearance is due to the alternation of source measurements with background measurements. The
FIGURE 18

(see page 111)

Graph of counting rate versus time for three different channel number groupings. For bottom to top, the corresponding energy ranges are: 25 to 102 keV, 107 to 258 keV, and 262 to 568 keV. Each segment was approximately 10 minutes long, and transit occurred at about 10:15 U.T.
FLIGHT 69-I  RAW COUNT RATE VS. TIME

FIGURE 18
effect of the near-zenith passage of Cyg X-1 can be seen as an apparent increase of the background rate at times near transit. (Cyg X-1 culminates only \(\sim 2.3\) degrees from the zenith at Alamogordo; see tables II and III.)

For the temporal analyses described below, the energy interval with the highest signal to noise (i.e., source to background) ratio was selected. This ratio, for channels 2 through 53 (corresponding to energies from \(\sim 30\) to \(\sim 250\) kev), is an unprecedented 1:2.

2. The Absence of Pulsed Radiation

Since the report of Oda and his colleagues indicated a pulsating source with a unique period of \(\sim 73\) milliseconds, a superposed epoch analysis was undertaken. In view of the strength of the source in the Cygnus region, and because the Uhuru data showed soft X-ray pulsations on the order of 25% of the total intensity of Cyg X-1, it was felt that the pulsations might well be detectable by using only a small portion of hard X-ray data. This procedure also relaxed the constraint on the accuracy with which the pulsation period had to be known. Hence the following procedure was employed.

Wide-range superposed epoch analyses were performed on the data of segment 25 (see figure 18). Cyg X-1 transited during this segment which was longer than most due to the
issuing of an "RA-STOP" command of 5 minute duration. (With the GS II system, "stop" and "fast" commands were employed to correct the telescope pointing for longitudinal balloon drift motions; since the balloon was drifting westward, "stop" commands were occasionally needed.) For an observation interval of \( \sim 15 \) minutes, one millisecond time resolution and an approximate period of 73 milliseconds, \( \Delta P \) must be \( \sim 0.1 \) microseconds. A period step size of one microsecond was actually used since the pulse width was not expected to be exceptionally narrow and since the \( \Delta P \) formula provides some leeway.

All period values between 71.9 and 74.1 milliseconds were examined using an increment of one microsecond. Hence a total of 2200 pulse profiles was computed and examined using the chi-square indicator.

Whenever a value of chi-square \( > 100 \) occurred, a special search was made using a finer period step and additional data. Segments 23 through 27 were used for these "closer look" analyses. (Approximately forty such closer looks were required, which is about the number expected from statistics.) The "background" segments 24 and 26 were included, since Cyg X-1 was only about 5 degrees off axis and was therefore reduced in intensity by only \( \sim 20\% \). In all cases, the interest-
ing features subsided when the longer data span was examined. Any real effect would be expected to be enhanced by the addition of more data.

RUG-RAG was not the only group pursuing this matter. Word reached Rice (long in advance of publication) that the Goddard Space Flight Center group had also observed soft X-ray pulsations, but at a different period. In fact, Holt et al. (1971) observed many frequencies in their periodogram, most of which could be attributed to harmonics and beating of two basic periods at \( \approx 0.290 \) and \( \approx 1.1 \) seconds.

The 290 ms period was also sought in the flight 69-1 data. It was possible that the 73 ms period deduced from the Uhuru observations was actually \( 4 \times 73 = 292 \) milliseconds. (A period of 73 ms is faster than the Uhuru sampling period of 0.096 sec. and had been inferred from an apparent beating effect.)

Using a step size of 4 microseconds, the data of segment 25 were again examined, this time for periods between 280 and 296 milliseconds (4000 searches). Again all high values of chi-square were checked with additional data and found to be purely random in nature. A later report of a 232 millisecond periodicity was also investigated, but no evidence for that periodicity was found either (only 20 searches were expended
on that effort).

As a result of these analyses (which represent a very substantial investment of computer time), it can be said that no more than two percent of the 30 to 250 kev flux from Cygnus X-1/X-3 was emitted (on the date of observation) as pulsed radiation at any of the periods which were examined.

This result rules out the possibility that Cyg X-1 is a "true" pulsar (unless it has a period outside the ranges searched). It does not, however, preclude the possibility that Cyg X-1 is highly variable, with a temporal behavior that is only quasi-periodic.

3. Upper Limits to Short-Term Fluxtuations

As discussed in section V-C, short term fluctuations can not be detected with good sensitivity when low counting rates are observed. Yet Agrawal et al. (1971) have reported the detection of rapid variations in the hard X-ray flux from Cyg X-1.

The data from flight 69-1 were subjected to the type of analysis described in section V-C. The results are shown in figure 19, where counting rate in the 30 to 250 kev energy region is plotted versus time, with the source-pointing data broken into 2-minute segments. Two large variations
Counting rate versus time for the 30 to 250 keV data obtained during the flight 69-1 Cygnus observation. Source-pointing observations have been broken into ~2 minute intervals, while background measurements have been averaged over ~10 minutes. Gaps in the plotted curve indicate that portions of the background data were deleted (for convenience) during the data reduction process. The largest fluctuation is only 3.5 standard deviations and occurs at about 11:04. The slow, overall increase, from 06:00 to 09:00, in the source-pointing count rate is due to a decrease in atmospheric attenuation of the Cygnus flux; the balloon rose ~2 mb during this period.
appear; deviations of 3- and 3.5-σ occur at 12:28 and 17:02 respectively. A three sigma deviation is virtually expected (probability of 14%), but the 3.5σ change is rather unlikely (probability of 2%).

This latter case is not sufficiently significant to be interpreted as a measurement of variability, but is does require that the upper limit on such variability be placed rather high:

\[
\left[ \text{variability (in times of the order } \sim 2 \text{ minutes)} \right] \lesssim 25%,
\]

of net flux observed from CYG X-1/X-3 for 30keV < E < 250keV.

Note that this upper limit is expressed as a percentage of the flux from the Cygnus region, not as a percentage of the total counting rate. The percent change in the total counting rate is, of course, smaller (\sim 9%) and agrees with the estimates made in section V-C for the sensitivity of this technique.

This technique is not sensitive enough to detect variability convincingly, and yet does not make a definitive statement regarding the absence of variations. A power spectral analysis of the data might reveal more clearly the nature of the temporal behavior, but such an analysis was not undertaken as a part of the present work since Cyg X-1 does not
appear to be a pulsar. (It is also felt that such an analysis would probably not produce significant results.)
VII. THE RELEVANCE OF THE PRESENT MEASUREMENTS

The developments which led to the acceptance of the currently favored rotating neutron star theory of pulsars were described briefly in section II. The original comments by Gold (1968) have been amplified by countless authors, and a review of specific models will not be attempted here. While there is general agreement on the basic energy source and timing mechanism for pulsars, there is no such agreement upon the detailed processes which account for the observed properties. It is perhaps too soon since the discovery of this phenomenon to expect the observational data to be classified in a manner which admits the selection of the more pertinent features for inclusion in theoretical treatments.

The basic pulsar mechanism is believed to be the rotation of a magnetic neutron star which is formed when the parent star catastrophically reaches the endpoint of normal stellar evolution and produces a supernova explosion. Estimates of the energy involved in such events range from $10^{48} - 10^{49}$ ergs, from the optical output of observed supernovae, to $10^{50} - 10^{52}$ ergs, from various theories which have been put forth to explain these events. Several authors (e.g., Gold (1969); Finzi and Wolf (1969) have noted that the energy stored in a neutron star is of the same order: $\sim 10^{49}$ ergs,
for a neutron star of one solar mass, radius - 10 km, and a rotation rate of 30 rev sec\(^{-1}\). Hence the rotating star provides both an accurate timing mechanism and a reservoir of energy. In addition to increasing rotation rate, the collapse of a normal star to the dimensions of a neutron star will also increase the strength of the star's magnetic field. The pre-existing field will be compressed, with the result (see e.g., Pacini 1967) that magnetic fields as high as \(10^{12}\) gauss are expected.

It is therefore easily imagined that the rapidly rotating, magnetic neutron star is a promising site for the generation not only of radiation fluxes but also of energetic particle fluxes. The precise region responsible for the observed pulsar radiations is the subject of much debate; the stellar surface and the velocity of light cylinder (the distance at which co-rotation with the star implies a linear velocity equal to the speed of light) are the two most popular sites, though regions beyond the light cylinder may also be important.

A. The Crab Nebula and PSR 0531+21 (NP 0532)

The discovery of the Crab Nebula pulsar seems to have solved the long standing problem of providing an energy source for the present day activity within the Nebula. Finzi and
Wolf (1969) have drawn attention to the fact that the rate of energy loss implied by the slowdown rate of the pulsar is in excellent agreement with estimates of the energy input required to explain the total nebular luminosity.

RUG-RAG flight 67-1 seemed to compound the energy balance problem for the Nebula by extending the observed energy spectrum into the gamma-ray region. Ellis (1967; see also Haymes et al. 1968a) revised the required maximum particle energy upward by a factor of ~30. Yet the same flight, through the analysis of Fishman et al. (1969a), later helped to alleviate this energy balance problem.

The 1967 period measurement (described in section VI-A) demonstrated the existence of the pulsed gamma radiation, verified the existence of the pulsar as early as 1967, and made possible an improved determination of the slowdown rate. At the time Fishman et al. (1969a) first announced their period measurement, the period slowdown rate was not extremely well known. The 1967 measurement not only reduced the uncertainty in dP/dt by a factor of ~3, but also revealed that the pulsar had not undergone any discontinuous period jumps of the size observed for the Vela pulsar.

The 1966 determination (also described in section VI-A) has extended to ~4.5 years the time interval over which
PSR 0531 is known not to have experienced large period discontinuities. (The post-discovery radio and optical observations now have such great precision that the 1966 period value cannot improve the dP/dt value.)

The pulsed spectrum determined from flight 67-1 is shown in figure 20 along with other X- and gamma-ray spectral measurements. The pulsar data, like those of the total nebular emission, appear well approximated by a power-law (of photon energy). The high-energy pulsar radiation may therefore be explained on the basis of synchrotron emission. The rotating neutron star apparently provides a source of energetic electrons (an electron energy power law spectrum is needed to reproduce the observed photon energy spectrum) for the steady emission. In addition to this, a fraction of the total photon emission (ranging from \( \sim 5\% \) at soft X-ray to \( \sim 50\% \) at gamma-ray wavelengths) is somehow modulated at the rotation rate of the pulsar.

B. The Vela Region

The first report of a discrete X-ray source in the Vela region of the galactic plane was made by Chodil et al. (1967) who designated it Vel XR-1. Gursky et al. (1969) later refined its location (referring to the object as GX 263+3, but
FIGURE 20

(see page 125)

Logarithmic plot of energy flux versus photon energy. All data except the solid line labeled as total Crab emission refer to the pulsar 0531+21 (NP 0532). This figure was reproduced from Kurfess (1971).
Figure 20

Energy flux (keV/cm² sec keV)

Photon energy (keV)

Total Crab Emission ~ 10 E⁻¹²

Fritz et al. (1971)

Ducros et al. (1970)

Fishman et al. (1969)

Kurfeess (1971)

Hillier et al. (1970)

Kinzer et al. (1971)
neither of these observations (at energies of 4 to 10, and 4 to 28 keV, respectively) yielded quantitative spectral information for the object. Cocke et al. (1969), at energies of 2 to 16 keV, saw only marginal evidence for a source at the location of Vel XR-1 and suggested that it might be a variable or short-lived X-ray emitter. Lewin et al. (1968) have apparently scanned this region (and may have observed a weak excess flux) but have published no results specifically pertaining to Vel XR-1. Hudson et al. (1971) have scanned neighboring regions with their OSO III satellite detector, but have apparently not made observations at the location of Vel XR-1.

A source of 0.1 to 1 keV X rays was observed by Grader et al. (1970) and designated as Vel XR-2. Though its location was not significantly different from that determined by Gursky et al. for Vel XR-1, the authors felt that it was probably not the same object. Vel XR-2 exhibited a very soft spectrum, while Vel XR-1 had been reported as being harder than the Crab Nebula (which has an $E^{-2}$ photon number spectrum). Bremsstrahlung and line spectra were fitted by Grader et al. to their data, but they deferred more extensive spectral analysis until more sensitive measurements could be made.

Attention has recently been drawn to this region of the
sky by several authors (see e.g., Maran et al. 1971) in connection with the Gum Nebula. This large, nearby nebula is \( \sim 30^\circ \) in diameter (some authors argue that it is even larger) and is centered on the Vela X supernova remnant. Brandt et al. (1971) have suggested that the Vela X supernova was responsible for the creation of the nebula. Figure 21 (which appears as figure 1 of Bunner [1971]) is a map of this region of the sky and shows that PSR 0833-45 is located within the Vela X remnant, as first noted by Large et al. (1968) who discovered the pulsar.

Recent measurements of this region have revealed an extended source of soft X rays. Indicated in figure 21 by the circle is the shell model derived by Seward et al. (1971) to fit their 0.3 to 2 keV data. (In a previous experiment, Palmieri et al. [1971], the same authors had obtained a similar result.)

It is interesting to note that Seward et al. found it necessary to postulate a point source, in addition to the shell source, in order to provide a good fit to all of their data. This point source must lie somewhere along a line which passes very close to the pulsar. (This line is not shown in figure 21; see Seward et al. [1971].)

The present measurement of hard X-rays from the Vela
FIGURE 21
(see page 129)

Sky map of the Vela pulsar region, reproduced from Bunner (1971). See figure for description of map.
A map of the Vela-Puppis region. The radio brightness contours are 2650 MHz isotherms from Milne (1968) and from Milne and Hill (1969). The X-ray source positions of LRL and ASE are shown. The large solid circle is a shell model used to fit the Vel XR-2 0.3 – 2 keV data of Seward et al. (1971). The dashed ellipse indicates the 0.2 – 0.3 keV emission. The accuracy of the location of the X-ray source Pup A is 0.3. Also shown is the center of a circumferential magnetic field pattern (Milne 1968a), the location of the pulsar PSR 0833-45 and the optical filaments (wispy lines).

FIGURE 21
region constitutes the first such measurement; all previously reported results have been at energies below \( \sim 25 \) keV. The results of section VI-B are shown in figure 22 along with the soft X ray measurements of Seward et al. (1971) and Bunner (1971). An examination of the figure indicates a possible hardening of the Vela spectrum between \( \sim 1 \) keV and \( \sim 50 \) keV, but since the present results were obtained with a 24\(^\circ\) - FWHM detector, it is by no means clear that the hard- and soft- X ray measurements refer to the same object.

C. PSR 0833-45

The Vela pulsar was discovered by Large et al. (1968) who determined its period to be \( \sim 89 \) milliseconds and noted its possible association with the Vela X supernova remnant. It became the subject of considerable interest when its period underwent an apparently abrupt increase in March of 1969, as reported by Radhakrishnan and Manchester (1969) and Reichley and Downs (1969).

This period jump set off much speculation regarding its possible causes. Greenstein and Cameron (1969) discussed the effects of differential rotation between core and envelope regions within a neutron star. The decrease in period had been attributed to the addition of infalling mass by Durney (1969), while Ruderman (1969) has put forth a theory based
FIGURE 22

(see page 132)

X- and gamma-ray spectrum of the Vela pulsar region. Measurements in the energy region from 0.2 to 2 keV were used to determine the soft X-ray power laws; Bunner (1971), flux = 3.9E^{-2.3} keV cm^{-2}sec^{-1}keV^{-1}; Seward et al. (1971) flux = 1.2E^{-3.2} (same units). The soft X-ray emission was localized to the vicinity of the Vela X supernova remnant (see figure 21), but the 24° - FWHM detector used in the present experiment could not isolate the hard X-ray object(s). Data from channel 2 have been added to the excess of figure 15, and the total excess has been plotted as two points (statistical significance: 3.4σ, for the point at 23 keV; 2.5σ for the point at 56 keV). Though these points are too closely spaced in energy to yield significant spectral information, they suggest a flux of the form: 300E^{-2.5} keV cm^{-2}sec^{-1}keV^{-1}. 
FIGURE 22
upon "starquakes" in a solid, crust-like outer layer of the neutron star.

A less exotic, and perhaps more believable, possibility has been pointed out by Michel (1970) as a feasible explanation of both the Vela jump and the smaller scale "discontinuity" that was observed for the Crab pulsar (Boynton et al. 1969; Richards et al. 1969). Hills (1970) has independently investigated the same effect, namely that of pulsar planetary systems. An obvious consequence of the models of Michel and of Hills is the periodic nature of the observable effects; the apparently abrupt period changes should recur regularly and should result each time in the same type of period behavior. Boynton et al. (1972) have attempted to interpret the period behavior of the Crab pulsar in terms of as many as three planets, but have not met with success. The recent detection of a second period jump (Lohsen 1971) is not likely to improve the case for a planetary system, since the magnitude of the second jump appears significantly smaller than that of the first.

Reichley and Downs (1971b) have recently observed a second period "discontinuity" for the Vela Pulsar. Though no detailed analysis has yet been performed, the planetary theory appears promising for this case; the magnitude of the second
jump is within 10% of that of the first. The time between jumps was $2.50 \pm 0.03$ years, as remarked in section II, and a rough estimate of the planetary orbit required to explain the behavior should now be possible. The existence of such a planetary perturbation to the observed pulsar period may bear directly upon the apparent discrepancy found here between the radio and X-ray pulsation periods.

Spectral information for the Vela region has been summarized in figure 23 which is a logarithmic plot of spectral flux density versus frequency. The apparent absence of optical emission from the pulsar may be analogous to the dip in the spectrum of the Crab pulsar in the infrared region, and soft X-ray pulsations may exist just below the sensitivity of the measurements.

An interesting comparison may be made with the predictions of a theory put forth by Sturrock (1970). His model of pulsar radiation mechanisms, which involves particle acceleration at the surface of the neutron star, predicts a detectable flux of X-rays from the Vela pulsar while optical emissions are precluded due to synchrotron self absorption. He predicts an average X-ray flux of $\sim 10^{-30}$ to $\sim 10^{-29}$ erg cm$^{-2}$ at $\sim 5$ keV, whereas the measurement described in section VI-C implies a flux of $\sim 10^{-29}$ erg cm$^{-2}$ at 25 keV.
Logarithmic plot of spectral flux density versus frequency, showing the steady nebula spectrum as well as that of the Vela pulsar. Nebula spectra are from Milne (1970) and Bunner (1971). The upper limits for the optical and soft X-ray pulsations are from Kristian (1970) and Bunner (1971), respectively. Radio pulsar data is from Downs et al. (1969) and Radhakrishnan et al. (1969). As discussed at length in the text, the hard X-ray data are the results of the present investigation.
However, in view of the considerations discussed in section VI-C, the possibility that the hard X-ray pulsation measurement is spurious cannot be ruled out. The apparent pulsations are just above the sensitivity threshold and consequently are of questionable statistical confidence. The 155 nanosecond period discrepancy casts further doubt on a straightforward interpretation of the measurement as evidence for the detection of PSR 0833. Yet such a measured discrepancy, if indeed real, surely contains important clues as to the nature of the mechanisms which operate at the site of the pulsar. In order to emphasize the importance of the period discrepancy and to place it in perspective with the other period behavior of the pulsar, the period history of PSR 0833-45 has been depicted in figure 24.

Gardner and Whiteoak (1969) have made an interesting observation of the pulsar at high radio frequency. They found evidence, in the pulse profile obtained from 4830 Mhz data, for a double pulse structure with two very narrow peaks spaced ~2 milliseconds apart. In view of their measurement, the X-ray profile obtained with the FAZSYNC/SEARCH program (see figure 25 and appendix D) at a period of 89.211285 ms. is rather intriguing. Though only bin 10 (lower curve, figure 25) is statistically significant (4.3σ), the two
FIGURE 24
(see page 139)

History of the temporal behavior of the period of PSR 0833-45. The period jump in 1969 March was observed at radio frequencies by Radhakrishnan and Manchester (1969) and Reichley and Downs (1969); the jump in 1971 August was detected by Reichley and Downs (1971b). The discrepancy between the radio period and the period of X-ray pulsations observed in present analysis is discussed at length in the text. The time axis is divided into years and $\frac{1}{12}$ years (≈ months; indicated by first letter of name of month). Inserts show each $\frac{1}{12}$ year further subdivided into tenths of $\frac{1}{12}$ year (≈ 3 days).
subsequent bins do hint at a double pulse with a 2 ms. spacing. (Bins 11 and 12 have chi values of 1.4 and 2.4 respectively.)

If the hard X-ray measurement is assumed to be valid, then a comparison with measurements of the Crab pulsar allows a determination of the secular behavior of the X-ray luminosity of pulsars. Pacini (1971) found that scaling indices (the exponent n in the relation: \( L \propto P^{-n} \), where \( L \) is the luminosity, and \( P \) the period of the pulsar) as high as \( n \approx 10 \) might be possible. If the distance to the Vela pulsar is taken as \( d \approx 500 \) parsecs (Kristian 1970) and the Crab Nebula is assumed to be at a distance of \( d \approx 2 \) kiloparsecs, then the exponent \( n \) is determined to be: \( n \approx 4.6 \pm 0.7 \), where the uncertainty in the distance to the Vela pulsar (i.e., a factor of \( d \approx 2 \)) is probably the largest source of error. This value of \( n \) is considerably smaller than the lower limit of 7 to 8 set by Kristian using his Vela optical upper limit and the optical Crab pulsar observations.

D. Cygnus X-1

In regard to the short term fluctuation analysis of section VI-D, the following remarks are made concerning the report of Agrawal et al. (1971). Those authors claimed that "pronounced variations" were observed, yet nowhere made a quantitative statement regarding the variations. A close
examination of the data presented in their figure 1 reveals at least three inconsistencies with their table 1. One of these errors propagated to figure 2 where the point for serial number 16 was plotted incorrectly at 324 instead of 189 min\(^{-1}\) (normalized excess). This point is one of two which were taken as indications of "pronounced variations." The other point, serial observation number 6, involves a comparison between rates in different pointing directions. Even if efficiency corrections (for viewing in each direction) are well known, possible pointing errors make such a comparison a rather risky endeavor. Comparisons of rates in the same pointing mode show no such drastic changes.

It seems likely, therefore, that Agrawal et al. have observed nothing more than the expected statistical fluctuations, as was the case in the analysis presented here. Although true variability in the hard X-ray flux from Cygnus X-1 may indeed be present, the statistical precision obtainable with currently available techniques does not permit the detection of such short-term variability.

The long term variability of Cygnus X-1 has been discussed by Haymes and Harnden (1970); and although those authors were of the opinion that the case for variability at hard X-ray energies was not a strong one, Overbeck and Tananbaum (1968)
have presented evidence for just such variability. Dolan (1970; 1971) has put forth a theory for the variability of Cygnus X-1 which is based upon an eclipsing binary system with a period of about three days. According to Dolan (1971), the model successfully accounts for the flux levels observed in all reported measurements. This model is even more intriguing in view of the recent developments described below.

Gursky et al. (1971) dramatically brought Cygnus X-1 to the forefront with their announcement of the detection of periodic soft X-ray emission from the object. However, other investigators have failed to find the \( \sim 73 \) millisecond pulsations reported from the Uhuru satellite observations. Holt et al. (1971), Rappaport et al. (1971) and Shulman et al. (1971) have all subsequently reported spectral analyses of their soft X-ray data from Cygnus. None has observed truly periodic behavior, yet all have detected significant short-term variability. Schreier et al. (1971) have now reported further analyses of Uhuru data on Cygnus X-1 and have found an explanation for the apparent discrepancies between the various temporal analyses.

As concluded from the superposed epoch analysis reported in section VI-D, Cygnus X-1 is not periodically variable with a period of 73 milliseconds. The Uhuru results indicate
no prolonged periodicity but rather periodicities which are present for a short time and then subside and do not recur. Hence short observations may yield significant peaks in the computed periodograms, but subsequent observations do not reveal significant power at those same frequencies. Such behavior would resolve the apparently conflicting reports of the authors cited above. Schreier et al. (1971) suggest that Cygnus X-1 comprises a new class of variable X-ray sources and report that another object (in the constellation of Circinus) detected by the satellite exhibits very similar properties. In a short-duration observation, apparently of the same Circinus object, Margon et al. (1971) have detected an apparent ~685 ms periodicity. If Schreier et al. are correct in classifying this object with Cygnus X-1, then further observations of Circinus XR-1 (as Margon et al. have named it) should fail to confirm true periodicity.

(It is interesting to note that Margon et al. (1971) have restrained themselves from speculating about a possible connection between pulsar MP 1530 and Circinus X-1; even though the pulsar is only ~4 degrees - or about 3 standard deviations - from the location they measured for Cir XR-1. The period of MP 1530 is 1.370 seconds, or precisely twice the period found in the soft X-ray data!)
Recent improvements in the location of Cygnus X-1 have permitted the detection of this object at radio frequencies, (Hjellming and Wade 1971; Braes and Miley 1971). The precise radio location has in turn permitted the selection of a candidate for the optical counterpart of Cygnus X-1. Although Kristian et al. (1971) have discounted the suggestion (made by several observers), a bright star within the radio position error does indeed appear to be related to Cygnus X-1. Recent studies of this star (BD+34°3815 = HDE 226868) by Bolton (1971) show it to be a spectroscopic binary with a period of 5.617 days, or about twice that deduced by Dolan (1971) from the X-ray observations. It is interesting to note that the separation between the two RUG-RAG observations of Cygnus (Haymes et al. 1968b; Haymes and Harnden 1970) is very nearly an integral multiple of the above period: (1969 Jun 5 05:15 C.D.T.) - (1967 Aug 29 23 :02 C.D.T.) = 645.26 days, or ~114.9 cycles of the alleged binary system. The fact that RUG-RAG observed nearly identical fluxes from Cygnus during the two balloon flights is consistent with such a binary system model.

E. Other Interesting Objects

There are at least four other objects that may be similar
to the three objects studied in this thesis. Circinus XR-1 has already been discussed (in the preceding sub-section), and Scorpius X-1 has been studied at great length by numerous observers and will not be discussed here.

The results of the Uhuru satellite data seem to indicate that there are many variable X-ray sources in the heavens, but Centaurus X-3 appears to be unusual. Giacconi et al. (1971) have detected periodic pulsations from this object and present fairly convincing evidence for the case that Cen X-3 is indeed a pulsar. The period of pulsations is so long (∼5 seconds) however, that a different mechanism may be responsible; Gribbin (1971) has revived the pulsating white dwarf model in an attempt to explain the properties observed from the satellite.

The radio pulsar PSR 0525+21 (also known as NP 0527), which has a period of ∼3.75 seconds and is located within about a degree of the Crab Nebula, has recently been reported to be a source of X-ray pulsations. The pulsation period observed in the X-ray data of a Naval Research Laboratory balloon flight (Sadeh et al. 1971) was ∼2.1 per cent slower than the corresponding radio pulsar period. Manchester (1971) has reviewed the radio properties of this pulsar. The fact that neither the data from Uhuru (R. Giacconi, unpublished
data) nor those of Kurfess (1971 and private communication) show evidence of X-ray pulsations, however, casts some doubt on the validity of the NRL results.
VIII. SUMMARY AND CONCLUSIONS

A series of balloon flight observations has been conducted for the purpose of investigating the X- and gamma-ray properties of three particular celestial objects. The experiments have yielded exciting new information regarding these objects and their relationship to the astronomical phenomenon known as pulsars.

The Crab Nebula contains a genuine pulsar which, as a result of the experiments, has been found to radiate at gamma-ray energies as well as at the radio, infrared, and optical frequencies observed by other investigators. The temporal behavior of this pulsar's pulsation period, while very complex and ill-understood at the finest time scales observable, has been shown to be approximately quadratic over a period of 4.5 years. The 1966 and 1967 measurements described here have precluded the possibility that the pulsar has undergone unrecovered period discontinuities on the order of 100 nanoseconds.

The discovery of hard X radiation from the central region of the Gum Nebula will undoubtedly prompt other X- and gamma-ray astronomers to turn their instruments on the Vela region. Until recently this region of the sky had been rather neglected; but the detection of X-rays from the as-
associated pulsar PSR 0833-45 should effectively put an end to that neglect. New understanding of the pulsar phenomenon will be required to explain the properties of the Vela pulsar described here. The different pulsation periods for radio and X-ray emissions is an unexpected result, but at least one pulsar theory predicted that the X-ray luminosity of PSR 0833 would permit its detection.

Cygnus X-1 is easily one of the most exciting topics of current investigations; rapid progress is being made toward the identification of a single object as responsible for its broad band emission from radio to gamma-ray wave lengths. Though the object had recently been tentatively linked directly to the pulsar phenomenon, this now does not appear to be the case. The 1969 experiment described here, as well as observations by several other groups, indicates that Cygnus X-1 is not a genuine pulsar. While it may be a closely related phenomenon, the object probably is not a rotating neutron star beaming pulsed radiation directly at earthbound observers. The hard X-ray flux from this object is not sufficiently variable, on a time scale of minutes, that such fluctuations are detectable from balloons using current techniques, even though Cygnus X-1 is the brightest object in the hard X-ray sky.
Most of the findings reported in this thesis may be regarded as certain; but in view of the striking nature of the result for PSR 0833, this observation must be regarded as tentative, pending its confirmation. Nonetheless, the implications of the measurement, should it be confirmed, are far-reaching. The apparent absence of optical emissions implies that the Crab Nebula is not the archetypal model for all pulsars. This is not a surprise; the Nebula is known to be virtually unique. Yet theorists insist upon using the Crab pulsar as the basis for their pulsar models. They are not to be censured for this; the Crab Nebula is probably the most exciting object in the sky. But perhaps the present measurement of the Vela pulsar, combined with other recent interest in the Gum Nebula, will serve to put the Crab Nebula in a more appropriate perspective.
Appendix A

Computers at Rice University

Two different computers were used in the work reported in this thesis. They are described here not to emphasize the particular machines actually used, but rather to indicate the type of equipment that was such an essential tool in the analysis. In view of the fact that the fields of high-energy astronomy employ a high degree of state-of-the-art technology, it may seem peculiar to single out computers for special praise. (Why not eulogize that technological triumph, the stratospheric balloon, which reliably carries instruments weighing over a ton to altitudes of up to 40 km?) The reason is that the computers were an integral part of the data analysis which is described rather than a part of the apparatus of the experiment itself.

The SDS-92 (manufactured by Xerox Data Systems, formerly Scientific Data Systems) is a small, high-speed, general purpose computer particularly well suited to data format conversions. It is easily interfaced with external equipment and is therefore quite versatile. Its priority interrupt system, parallel input capability, and real time clock made it ideal for the task of digitizing the analog data obtained
in the RUG-RAG balloon flights. Its ready availability also figured in its usefulness.

The Rice Computing Center (otherwise known as the Institute for Computer Services and Applications) maintains a Burroughs B5500 computer system. It is a fairly large, high-speed, general purpose computer of early second-generation vintage. Any large computer would have sufficed.

The computer did, however, make possible an amount of analysis not feasible by any other means. Though specialized hardware exists (e.g., a multichannel analyzer operated in the multiscaling mode) which is capable of real-time superposed epoch analysis, such a technique proceeds at real-time speed. Each time the data are searched for a different period with such a technique, the entire data record must be replayed. Not only does a computerized technique speed up the analysis, but it also makes possible the attainment of much greater period resolution. With the real-time analysis a frequency synthesizer of high stability must be employed to achieve the resolution, while with the computer analysis the period resolution follows automatically from the precision of digital computation.

One other tool of unusual utility is the Hewlett-Packard Calculator, Model 9100A. Equipped with a printer and an
X-Y plotter, this desk-top, programmable calculator makes it possible to accomplish in a day's time that which could otherwise take several days if a large computer were used. It has been particularly useful for data fitting procedures where graphical displays are quite helpful.
APPENDIX B

Application of the MAXCHI and Chi-Square Tests

As indicated in section V, two different procedures were used to characterize the results of the superposed epoch analysis. The use of single-number indicators is preferable to an examination of the entire superposed epoch function (or pulse profile), primarily because it is more reliable (there is less chance of a significant feature being overlooked).

1. MAXCHI

MAXCHI is obtained simply by selecting the highest bin in the superposed epoch function, SE(t_i), and expressing its deviation from the mean number per bin in terms of the standard deviation. In practice, all deviations are calculated (for use in the $\chi^2$ - test) and the largest deviation is chosen. In terms of the number of counts, $n_{\text{max}}$, in the highest bin and the mean number per bin, $n_{\text{mean}}$, MAXCHI is defined as:

$$\text{MAXCHI} = \frac{n_{\text{max}} - n_{\text{mean}}}{\sqrt{n_{\text{max}}}}$$

This definition assumes that Poisson counting statistics are
applicable, so that the standard deviation associated with the number of counts in a bin is well approximated by the square root of that number.

The applications of statistics to nuclear (or other similar, random) processes is treated very nicely in chapters 26 - 28 and appendix G of Evans (1955), and a discussion is found there of the convergence of the Poisson distribution to a normal or Gaussian distribution in the limit of a large mean number of events. The normal distribution provides a convenient basis for the development of an intuitive feeling for experiments which attempt to measure differences from some average value. Two such experiments are discussed in this thesis: (1) the measurement of a time-averaged flux from the difference of two counting rates (i.e., source and background rates), and (2) the measurement of periodic pulsations in a counting rate by the identification of significant variations from a "flat" pulse profile. In experiments of this type, the measurement may be characterized by the value of chi, which is defined as: \[ \chi = \frac{\text{measured excess}}{\text{standard deviation}} \]

The probability of a given value of chi may be computed from the normal distribution (or looked up in a table). For instance, a "one sigma result" has \( \chi = 1 \) and a probability of \( \sim 32\% \) that such a deviation from the average value (of
whatever it is that is being measured) is due merely to chance. Clearly, a "one sigma result" is not very convincing; but nearly anyone would agree that a "5-σ result" is genuine, since the probability that $\chi = 5$ by chance is only $6 \times 10^{-7}$. (The probabilities given above include a factor of two due to the fact that $\chi$ may be either positive or negative.)

In practice, probabilities are often used to predict the number of occurrences of a particular event. For the superposed epoch analysis, the event of interest is a large (positive) deviation from the mean number of counts per bin. In this case, the number of bins examined corresponds to $n$, the total number of trials. Since there are $P$ bins per pulse profile (where $P$ is the period expressed in milliseconds) and one profile for each period that is examined, there are a total of $n$ trials where $n = P \times (number\ of\ periods\ examined)$. The total number of trials multiplied by the probability of a given event yields the expected number of occurrences of that event.

As an example, consider the prediction of the number of occurrences of $MAXCHI \geq 4.1$. Assume 31 different periods are examined at a period of $\sim 89$ milliseconds. The total number of trials therefore is $n = 89 \times 31 = 2759$. The prob-
ability that MAXCHI $\geq 4.1$ is found to be $\sim 2 \times 10^{-5}$, hence the predicted number of occurrences for MAXCHI $\geq 4.1$ is:

$$(2 \times 10^{-5}) \times 2759 \approx 0.055.$$ It is expected that $\sim 18$ times as many searches would be required to yield one occurrence of a MAXCHI $\geq 4.1$ event.

Now consider the triple-bin profile discussed in section VI-C. In "discovering" the 4.8-$\sigma$ bin in this profile, the same 31 periods would have been searched, but in this case, the number of bins per profile would be $\sim \frac{P}{3}$ or $\sim 30$. Hence the total number of trials would be less, while the deviation is greater. The probability of MAXCHI $\geq 4.8$ is found to be $\sim 8 \times 10^{-7}$, and $n = 31 \times 30 = 930$, which predicts only $\sim 10^{-3}$ such events!

That the likelihood of the 4.8-$\sigma$ event should be less than that of the 4.1-$\sigma$ event is illustrated by the "high-low" effect mentioned in part one of appendix D. When the bins are widened from one to three milliseconds, the high-low nature typically exhibited by adjacent bins will cause many of the large deviations to "wash out" into smaller deviations from the mean. This is how statistics must work: when the number of trials (i.e., bins) is decreased the number of large excursions from the mean must also decrease.
2. Chi-Square Test

The chi-square test is usually applied in order to find a function which best fits the experimental data. Quite the contrary, in the analysis described here, the test is applied to find the data which fits a function worst. The function used is the mean value.

Random data are expected to have a flat pulse profile, so that a fit of the profile to the mean value will be relatively "good" and yield a low value of chi-square. (In fact, chi-square is minimized as a criterion for the best fit obtained in the usual application of the test.) The value of $\chi^2$, for random data, is distributed about its mean value of $\sim \nu$ where $\nu$ is the number of degrees of freedom. For the present case $\nu$ is number of bins in the pulse profile minus one, since a one parameter fit is used.

When a feature is present in the profile, the value of $\chi^2$ will increase; and it is therefore the largest value of $\chi^2$ that is sought in this type of analysis. When a large value of $\chi^2$ is found, its significance may be assessed by computing the probability associated with the given values of $\chi^2$ and $\nu$, but an alternative method for interpreting a $\chi^2$-value is to express it in terms of an equivalent value of MAXCHI. Several approximate methods exist for finding
MAXCHI such that:

\[ \text{probability} \left\{ \chi^2 \geq y \right\} = \text{probability} \left\{ \text{MAXCHI} \geq x \right\} \]

One convenient method is the cube root approximation (see e.g., Abramowitz and Stegun [1965], p. 958):

\[ x = \left[ \frac{y}{u} \right]^{1/3} - \left[ 1 - \frac{2}{9u} \right]^{1/3}, \text{ for } u > 30. \]

With this approximation, a value of \( \chi^2 = y \) may be characterized as an "x sigma result".

For example, consider the \( \chi^2 \) versus period plot of figure 12. Chi-square peaks at a value of \( y \approx 95 \), and there are \( u \approx 32 \) degrees of freedom. Hence \( x \approx 5.3 \), and such a value of \( \chi^2 \) may be thought of as roughly equivalent to a "five sigma result".
APPENDIX C

The Performance of Detector GS II-A During Flight 70-4

The fact that RUG-RAG has used two different detectors of the Gammascope II (GSII) design has been discussed by Glenn (1969), who labelled the two instruments A and B. GS II-A was used for flight 67-1 and after the flight was sent back to the manufacturer for modification. (The amount of absorbing material within the viewing aperture was reduced by modifying the mounting for the phototube which views the central crystal; see figure 2). After the modification, the detector was maintained as a back-up. It made a round trip to Australia in 1968, but was not flown during that expedition. By the time it was pressed into service for the 1970 expedition to Argentina, the guard crystal had become rather badly fractured; the damage occurred in transit either to or from Australia.

Though the guard crystal showed many fissures (visible in four or the six viewing windows), the detector performed quite well in the laboratory, exhibiting a slightly better energy resolution than GS II-B as had been noted by Glenn (1969). In an attempt to compensate for the degraded light gathering capability of the guard crystal, the gain of the
associated electronics was set rather high; and the threshold, rather low.

Shortly after launch, both on flight 70-3 and 70-4, detector A appeared to become noisy. (Flight 70-3 was aborted, by command, at an altitude of \(\sim 80,000\) feet due to a mechanical failure of the outer gondola). The "noise" commenced rather abruptly at an altitude of about 25,000 feet, and continued until the detector was turned off by command. Twice, while the balloon was at float altitude, A was commanded on briefly, and each time the "noise" resumed immediately. Consequently, the detector was left turned off for the remainder of the flight. There were, however, two other anomalies during the 15-hour observation at float altitude.

The first was associated with the azimuth servo system, which apparently turned itself off midway through the Vela observation. An "azimuth on" command (see table X) was issued when the trouble was detected (it took several minutes for the gondola to drift noticeably away from the nulled position). This command had no effect. A "power amp #2" command was then issued, since power amplifier #1 had been employed in the servo loop previously. (Dual power amps are provided for just such emergencies!) This did correct the situation; the gondola immediately regained the proper atti-
<table>
<thead>
<tr>
<th>COMMAND</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PA #1</td>
</tr>
<tr>
<td>2</td>
<td>PA #2</td>
</tr>
<tr>
<td>3</td>
<td>RA MODE CHANGE</td>
</tr>
<tr>
<td>4</td>
<td>RA FORWARD</td>
</tr>
<tr>
<td>5</td>
<td>RA REVERSE</td>
</tr>
<tr>
<td>6</td>
<td>DEC UP ON</td>
</tr>
<tr>
<td>7</td>
<td>DEC OFF</td>
</tr>
<tr>
<td>8</td>
<td>DEC DOWN ON</td>
</tr>
<tr>
<td>9</td>
<td>AZIMUTH ON</td>
</tr>
<tr>
<td>10</td>
<td>AZIMUTH OFF</td>
</tr>
<tr>
<td>11</td>
<td>COMMUTATOR OFF</td>
</tr>
<tr>
<td>12</td>
<td>MANUAL TIMER</td>
</tr>
<tr>
<td>13</td>
<td>AUTOMATIC TIMER</td>
</tr>
<tr>
<td>14</td>
<td>DET B OFF</td>
</tr>
<tr>
<td>15</td>
<td>DET A OFF</td>
</tr>
<tr>
<td>16</td>
<td>COM. REC. TEST -2.5v</td>
</tr>
<tr>
<td>17</td>
<td>60 HZ OFF</td>
</tr>
<tr>
<td>18</td>
<td>60 HZ ON</td>
</tr>
</tbody>
</table>

-161-
tude. Since power amp #1 worked properly when tried again later during the flight, this problem was diagnosed as overheating. If this diagnosis is correct, which seems probable, then it is unlikely that this anomaly would have affected the gamma-ray data. Nor does it seem likely that the detector A malfunction was related to the servo system problem.

The other anomaly has been designated as the "A flash effect". Intermittently, throughout the entire time that detector A was "turned off", the pulse height analyzer labelled a small fraction of the counts with the identifier bit set to "A". This effect is believed to be understood as a combination of two different processes. First, the identifier-bit circuitry sometimes mislabelled overflow counts (those with energy losses exceeding the upper threshold) from detector B as A-counts. Second, the method used to turn off the detectors was not 100% effective; occasionally the signal from the A central crystal was able to pass through the relay which was supposed to be an open circuit (possibly an inductive effect). Though the power to the A guard-crystal electronics was disrupted by the "A off" command, the central crystal remained powered, but with its output supposedly disconnected from the analyzer.
If the situation was indeed as described above, then the data from detector B were not affected by the "A flashes", except for the overflow channel. The "A flash" effect was quite small, in terms of total number of counts involved, and could not have accounted for the azimuthal asymmetry that was observed in the detector B overflow counting rate (Johnson et al. 1972). The "detector A" data, from the Galactic center portion of the flight, were processed separately from, but in a similar fashion to, the detector B data. The results of this analysis (Johnson 1972) are consistent with the above diagnosis of the "A flash" effect; i.e., the "detector A" data did not show a correlation with telescope pointing direction.

The above comments are probably sufficient justification for dismissing the "A flash" effect as a potential hazard to the analysis of the B data, yet one likes to feel that he understands his problems. The following discussion is directed toward the aim of understanding the problem.

There are several further pieces of information which bear on the "A flash" effect.

(1) An "A" spectrum, taken during the time that the detector was "turned on", looks remarkably similar to what would be expected from a detector with its anticoincidence
circuitry turned off, i.e., the count rate is higher by $\sim 3$, but the spectral shape is definitely not that of true "noise".

2. The effect commenced too rapidly during ascent to be due to a pressure or temperature effect upon the electronics, yet it undoubtedly was altitude dependent.

3. The effect recurred on the second Argentina flight, even after very extensive measures had been taken to prevent it. It seems unlikely, therefore, that it was a true malfunction.

4. During flight 71-1 (launched from Palestine 1971 July 1), a similar problem occurred but this time affected both detectors.

All of the above may be understood in the context of the following theory.

The sea-level flux of atmospheric X rays cuts off below $\sim 100$ kev (see, e.g., Harnden, 1971, figure 5), presumably due to the dominance of photoelectric absorption over production mechanisms at low energies. Yet at altitudes above 20,000 feet, the X-ray flux rises sharply with altitude (see, e.g., Glenn 1969). The "A flash" effect could have been the response of the detector to the suddenly increasing flux of low-energy X rays. With its high gain and low threshold,
the guard crystal electronics could easily have become "saturated", with the result that the reject circuitry would "lock up" and become totally ineffective. One of the changes made to detector B prior to flight 71-1 was the lowering of its guard crystal threshold, hence it too became subject to this effect.

It is indeed unfortunate this problem evaded solution for three flights. The success of flight 71-2 (launched 1971 November 20, see Johnson 1972), however, is a further indication that the effect has finally been properly diagnosed.

The flight 70-4 data, whose analysis is reported in this thesis, are therefore believed to be free of contamination due to instrumental anomalies.

One further point must be made. Turning off detector A changed the input impedance to the pulse height analyzer causing a slight shift in the electronic gain of the system. This effect was anticipated, and pre-flight calibration spectra were taken for each detector operating with the other turned off. However, the statistical precision of the "A off" calibration was not sufficient to determine the energy to better than about $\pm 2$ channels. (The radio-isotopes used for the energy calibration were not viewed long enough.) Hence energy values determined from the flight data have an associated uncertainty of about $\pm 15$ keV.
APPENDIX D

Troubleshooting the 4.1 σ Glitch

The following two questions were inspired by the pulse profile shown in figure 16, and this appendix is devoted to answering these questions:

(1) Assuming the feature in the profile is real and truly represents the detection of the pulsar, what improvements can be made in the analysis in order to enhance the appearance of the effect?

(2) If the effect is not real, can it be attributed to some error in the analysis, or can refinements be made which will make the feature appear less pronounced?

1. Refinements to the Superposed Epoch Technique

As discussed in section V, an approximation had been made in keeping track of the correct phase of each X-ray event. Since it was possible that this approximation was broadening the feature in the pulse profile, a more exact method was substituted. A quadratic polynomial of time was fitted to the pulsation frequency behavior determined from the Doppler shift plus intrinsic period changes. (The period behavior was
was inverted by Doppler shifting the pulsation frequency instead of period.) This expression was then integrated analytically to give phase as a cubic polynomial of time. Then, in the program (called FAZSYNC/SEARCH) which calculated the superposed epoch function, this polynomial was simply evaluated at the time of each X-ray event, thereby giving the precise phase of each detected X ray. Due to a change in the time arbitrarily chosen as zero phase (FAZSYNC/SEARCH define zero phase at $t = 06^h 50^m 0^s.019$ U.T., whereas CHI/SEARCH defines it to be $t = 06^h 50^m 0^s.000$ U.T.), features in the profiles obtained by FAZSYNC are shifted ahead 0.019 seconds (19 bins) from corresponding features in the profiles of CHI/SEARCH.

Figure 25 is a plot of three different pulse profiles which allow two interesting comparisons. The 89.211275 ms profile due to CHI/SEARCH has a MAXCHI of 4.1, while the FAZSYNC profile obtained for 89.211285 ms has MAXCHI = 4.3. Though this difference is not large enough to be significant, it is intriguing not only that MAXCHI increased when the more accurate method was applied, but also that the period thereby determined was shifted ten nanoseconds closer to the expected radio pulsar period. Furthermore, bin 39 is rather prominent in the CHI/SEARCH profile, but FAZSYNC
FIGURE 25
(see page 169)

Pulse profiles obtained from an analysis of channel 3-10 data. Note that the lower two curves have been shifted 19 bins to compensate for the different phase = 0 conventions used by the two programs. The apparent period $P$ at which the data were searched is indicated for each curve, as is the program used. Attention is called to bins 12, 13, and 14 of the upper two curves, and bins 10, 11, and 12 of the bottom profile. For each curve, the solid line indicates the mean count rate, and the dashed line indicates the contribution from background.
shows that this prominence was due to chance. While bin 39 is high, bin 38 is low in the upper curve. The FAZSYNC profiles smooth out this high-low effect, leaving bins 10 through 12 as the only eye-catching feature. (Note that features in the lower curve are shifted ~3 bins from the other two profiles. This is due to the fact that a change in the period also shifts the phase by $\Delta t \approx \frac{T\Delta P}{P}$).

The above answer to question (1) has enhanced the appearance of the pulse profile slightly, but the difference is not really significant. Another answer to question one is the inclusion of channel-2 data. This additional data increases the total number of counts by 9% yet leaves the significance of the 3-bin feature unchanged at the 4.8 - $\sigma$ level. (All indications point to the interpretation of channel 2 as valid data; yet the correction factors are so large at this low energy ~20 keV , that one hesitates to use the channel for flux determinations.)

2. Breaking up the Data

One test that sometimes works for isolating the spurious nature of peculiarities which turn up as the result of a superposed epoch analysis is the dividing of the data into several contiguous sections. If the effect is indeed spurious,
it may be due entirely to some abnormality of a small portion of the data. On the other hand, a genuine effect is likely to be present, at a reduced level, in all sections of the data.

Figure 26 represents the Vela observation time-line and shows, in addition, the results obtained from a data dividing process. The numbers indicated in the upper portion of the figure refer to the single bin excess found at a period of 89.211285 with the program FAZSYNC/SEARCH. Though segment V5 is considerably higher than the other three segments, all four show deviations above the mean; and excluding segment V5 from the analysis still results in a MAXCHI of 2.5. Furthermore, as indicated in table XI, segment V5 is expected to be favored on the basis of relative exposure to extraterrestrial flux. When allowances are made for the different viewing times and the varying atmospheric attenuation, V5 is seen to be about twice as "efficient" as the other three segments. A detailed examination of the data obtained during segment V5 failed to show any abnormalities such as instrumental - or telemetry-induced noise.

The conclusion drawn from the above is that the effect (i.e., the 3-bin "pulse" in the pulse profiles) is fairly well spread out over the entire observation. While the ef-
Time line for the Vela portion for flight 70-4. The pressure altitude (in millibars) versus time is indicated in the lower portion of the figure. For the time axis, note that: U.T. = A.D.T. + 3 hours. The letters, S, A, and B are used to indicate the pointing mode as dictated in real time by radio command and stand for: source pointing, background pointing, and detector A turned on (also in source pointing mode), respectively. Segment names are indicated by two to four character labels. The numeric digit (which follows the letter "V" indicating Vela data) counts the observation intervals with different telescope orientations: odd digits indicate source pointing; even digits, background pointing. Seven observation intervals were obtained, four source and three background. Alphabetic characters preceding the letter "V" indicate segmentation introduced during the computer processing for the purpose of maintaining phase coherence in the superposed epoch analysis. Alphabetic characters at the end of the label indicate segmentation required because of "A-on" intervals (see appendix C). The upper portion of the figure indicates the results of analyzing various pieces of the data separately; see appendix D, part 2, for a detailed
description. The transit time of PSR 0833 (at the location of the balloon) is indicated by the vertical line across the time axis.
### TABLE XI

**RELATIVE EFFICIENCIES OF VELA-VIEWING SEGMENTS**

**FLIGHT 70-4**

<table>
<thead>
<tr>
<th>Segment</th>
<th>Mean Atmospheric Path*</th>
<th>Observation Time (min)</th>
<th>Effective时间† (min)</th>
<th>Relative Efficiency‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>1.50</td>
<td>65</td>
<td>14.7</td>
<td>39</td>
</tr>
<tr>
<td>V3</td>
<td>0.85</td>
<td>63</td>
<td>23.7</td>
<td>62</td>
</tr>
<tr>
<td>V5</td>
<td>0.71</td>
<td>82</td>
<td>38.3</td>
<td>100</td>
</tr>
<tr>
<td>V7</td>
<td>0.71</td>
<td>57</td>
<td>23.9</td>
<td>62</td>
</tr>
</tbody>
</table>

*units are mean range in air for E ~30 keV photons

†defined as: \[ t = \int_{t_1}^{t_2} \exp \left[ -\frac{L \sec ZA}{R} \right] \, dt, \] where \( L \) is the altitude in gm/cm², \( R \) is the range in air (gm cm⁻²), and \( ZA \) is the zenith angle

‡defined as the ratio of effective time to the effective time of segment V5
fect is somewhat stronger in segment V5, this is no indication that the effect is not a real one.

3. Possible Instrumental Periodicities

The confusion of instrumental effects with those due to the natural phenomenon under investigation is not unprecedented in the recent pulsar history. The "first optical pulsar", as the radio (only!) pulsar CP 1919 was once billed, was subsequently determined to have a period related to the rotation rate of a mechanical part of the recording system used to detect the "optical pulsations".

The results of part 2 of this appendix place a rather rigid constraint on any instrumental effect which might be operating on the data. The fact that the observed effect is spread throughout the data requires a very accurate time reference for any such spurious source. In fact, the "Q" (ratio of frequency to frequency width) must be of the order \( \frac{0.089 \text{ sec}}{30 \text{ nsec}} \approx 3 \times 10^6 \), which would require a temperature-stabilized oscillator if it were to be produced electronically. It is unlikely that a mechanical system could resonate with such a high "Q".

One possible source of instrumental interference is the hour-angle drive circuitry. (See Harnden [1971] for a more detailed description.) A D.C. stepping motor is used to
drive the telescope about its polar axis at the apparent sidereal rate. Since this rate is varied according to the longitudinal drift motion of the balloon, the circuitry provides for several discrete pulse rates, with periods (between successive drive pulses) in the range 368.6 to 317.0 ms. (see table IV; flight 70-4 was drifting west). Curiously enough, 4 x (the measured period of the X-ray pulsations) \( \approx 356.8 \) ms; this is a possible period for the stepping motor (the driving oscillator had drifted from \( \approx 542 \) hz. thereby increasing all periods by \( \approx 3.0 \) ms.).

It is not too difficult to imagine that the motor pulses could somehow affect the X-ray counting rate, since transient current spikes and voltage spikes are associated with the pulsing of the motor. However, great care was taken to isolate the pulse height analyzer from such effects.

While the above postulated effect might have occurred, there is convincing evidence that it in fact did not. In the first place, the motor was always operated in the period range below 335 ms., quite removed from the postulated 356.8 ms. periodicity. Furthermore, the driving oscillator was drifting by about 0.1% per hour (due to temperature variation), which implies a time-interval dependent \( Q \) of:

\[
Q \approx f \div (t \text{ in hours} \times 10^{-3} \text{ f per hour}) \approx 4 \times 10^6 \div (t \text{ in seconds}).
\]
If an instrumental peculiarity were to generate the observed effect during some short time interval, however, then the Q required would be smaller:

\[ Q \approx \left( t \text{ in seconds} \right) \div 0.003 \text{ second phase interval} \approx 300 t. \]

Equating the Q of the oscillator to the Q required to produce the effect, one obtains: \[ 300 t \approx \frac{4 \times 10^6}{t} \], which implies \( t \approx 100 \) seconds. All the effect would have to be concentrated in a 100-second interval if it were to use the stepping motor oscillator as its time base. There is no 100-second portion of data (even in segment V5) that contributes disproportionately to the observed pulsation.

As a precaution against instrumental effects, the data were searched at 2, 3, . . . ., 11 times the period of the pulsations (89.211280 ms. \( \pm \) 10 nsec) in order to check the hypothesis that a harmonic of some slower periodicity had been observed. No significant deviations resulted.

The \( \sim 33 \) minutes of background data also were examined for the \( \sim 89 \) millisecond periodicity. These data failed to show any significant deviations from flat pulse profiles.

4. Mistakes in the Doppler Correction?

Since the pulsar-like feature resisted all attempts to attribute it to an instrumental or data analysis artifact,
the investigation turned to the question:

Could some error in the Doppler correction, or some overlooked effect, be responsible for the period discrepancy, which consequently would be apparent rather than real?

The program DOPPLER/SHIFT was used to calculate the velocity component (along the line of sight to PSR 0833) of the balloon relative to the heliocenter. The program uses the subprogram package described by Ball (1969) and has been checked against more accurate, barycentric calculations performed at the Jet Propulsion Laboratory by Reichley and Downs (1971a). The agreement of DOPPLER/SHIFT with the barycentric calculations is well within the uncertainty of \( \pm 0.005 \text{ km sec}^{-1} \) estimated by Ball for the subprogram package. Consequently the only remaining source of potential error in this calculation would be the use of improper input data (e.g., bad celestial coordinates for PSR 0833). As remarked in section V-D, RUG-RAG is (painfully) aware of the importance of using precise celestial coordinates. The coordinates of Reichley and Downs (taken from Chiu et al. 1970) were precessed to the date of observation as shown in table XII.

Other input data are the time of observation and the geographic location (including elevation) of the observer.
<table>
<thead>
<tr>
<th>EPOCH (U.T.)</th>
<th>RIGHT ASCENSION</th>
<th>DECLINATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950 (Jan 0.0)</td>
<td>08( ^{h} )33( ^{m} )39( ^{s} )09 ± 0( ^{s} )05</td>
<td>-45( ^{\circ} )00'05''3 ± 0''2</td>
</tr>
<tr>
<td>1970 (Nov 25.3)</td>
<td>08( ^{h} )34( ^{m} )22( ^{s} )34</td>
<td>-45( ^{\circ} )04'06''3</td>
</tr>
</tbody>
</table>
The time was known very accurately, and the location was known to within $\pm \frac{1}{8}$ degree in latitude and longitude and $\pm \frac{1}{2}$ km in altitude. The effects of uncertainties of this size in location have been investigated and correspond to changes in the Doppler-shifted period of less than 1 nano-second.

It therefore seems virtually certain that the Doppler shift was computed properly. There remains the possibility, however, that the shift was improperly applied.

The velocity component, $v$, computed by the subprogram package was used in the classical Doppler shift expression:

$$P = P_0 \left[ 1 + \frac{v}{c} \right].$$

With the sign of $v$ as defined by DOPPLER/SHIFT (negative for motion toward the pulsar), then $P_0$ is the heliocentric period and $P$ is the apparent period. The use of the wrong sign for $v$ would, in the case of the Vela observation, introduce a very large error ($2 \times 4474$ nsec $\simeq$ 9 microsec); but the proper sign was used.

The "bookkeeping" involved in matching the Doppler shift computed for time $t$ with the data obtained at time $t$ is rather trivial; hence it seems unlikely that an error would have been made here. Also, any gross timing mistakes (like a $\pm 1$ hour confusion of Daylight and Standard Times) are ruled out, since hour angles are also subject to such errors. All
three observed objects, Vela, Sco X-1 (see Haymes et al. 1972), and the Galactic Center (see Johnson et al. 1972), were indeed detected; an hour angle error of ±1 hour would have removed the objects from the field of view.

As indicated in section VI-C, the motion of the balloon relative to the ground station effectively introduced an additional Doppler shift due to the increasing propagation delay as the balloon receded from the station. This effect goes in the same direction as the heliocentric-to-observed correction, since in the Doppler formula $P$ is the "actually observed period" and $P_0$ is the "would have been observed if the balloon were not moving" period. It is $P_0$ that can then be translated to the heliocenter with the calculated value of $v$, not $P$. Hence $P_0$ must first be deduced from $P$ as:

$$P_0 = P - P_0 \times \frac{v}{c} \approx P(1 - \frac{v}{c})$$

and the effect is indeed seen to reduce the inferred heliocentric period. It should be noted, however, that this is a small effect (~5 nsec) compared to the estimated uncertainty in the measurement (~15 nsec).

5. Timing Considerations

The Astrodata Time Code Generator time base was proven accurate by the WWVH (and WWV) reception. A special, tuned rhombic antenna was constructed so that it was aimed at WWV
(Colorado: ~5740 st.mi., at a heading of ~32° west of north); WWVH (Hawaii: ~7300 st.mi., at a heading of ~75° west of north) was also in the beam width of the antenna. That first, WWVH, then WWV, and then again, WWVH were received during flight 70-4 was inferred from an analysis of the "tick" arrival times. Superimposed on a linear drifting of the arrival times (which indicates a constant frequency standard offset), was an apparent discontinuity. For a forty minute period, the ticks arrived 8 milliseconds early, but continued the linear drift. At the end of ~40 minutes, another discontinuity occurred, with the tick arrivals picking up again where they would have been (with the drift extrapolated) had there been no discontinuity. This 8 ms. discrepancy is nicely explained by the difference in propagation times from Hawaii to Argentina and Colorado to Argentina:

\[(7300 \text{ mi} - 5740 \text{ mi}) \div (186 \text{ mi per ms}) \approx 8.4 \text{ ms.}\]

The frequency standard of the time code generator differed from the WWV standard by: (4 ms.) \div (5 hours) \approx 2.2 \times 10^{-7}, or one part in 4.5 \times 10^6. This is a factor of ~20 off the specifications, but does not seem unreasonable since the instrument had been in the field for several years without recalibration.

The conclusions reached from the analysis of the WWV(H)
tick arrival times are:

(1) Timing resolution for the Vela observation was maintained at the nominal ± 1 millisecond level.

(2) Frequencies measured with the time base are, when corrected by a factor of $2.2 \times 10^{-7}$, at least as accurate as one part in ten million.
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