NASA- CR-189325

X-Ray Studies of the Hyades Cluster
NASA Contract NAS5-32070

Final Report

Submitted To:

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt Road
Greenbelt, MD 20771

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October 8, 1993

(NASA-CR-189325) X RAY STUDIES OF THE HYADES CLUSTER Final Report (Lockheed Aircraft Corp.) 22 p

N94-29001

Unclas

G3/89 0002588

1. Summary

We report the results of a complete survey of the Hyades cluster using the ROSAT All Sky Survey (RASS). Over 900 sq degrees of the sky were examined in the course of this study. Nearly 200 Hyads were detected down to a limiting L_x of $\approx$ 1–2 $\times$ 10^{28} erg s $^{-1}$. Binarity is shown to play a key role in the X-ray luminosity function of the cluster.

2. Introduction

The Hyades cluster occupies a unique position in both the history of astronomy and at the frontiers of contemporary astronomical research. At a distance of only 45 pc, the Hyades is the nearest star cluster in the Galaxy which is localized in the sky: the UMa cluster, which is closer, but much sparser, essentially surrounds the Solar neighborhood. The Hyades is the prototype cluster for distance determination using the "moving-cluster" method, and thus serves to define the zero-age main sequence from which the cosmic distance scale is essentially bootstrapped. The Hyades age (0.6-0.7 Gyr), nearly 8 times younger than the Sun, guarantees the Hyades critical importance to studies of stellar evolution.

It is less generally appreciated that the Hyades also occupies a critical place in the study of stellar activity evolution on the main sequence. Over the past 25 years, greatly improved stellar rotation velocity measurements have become available for stars less massive than the Sun, while at the same time, optical spectroscopy of chromospheric diagnostics such as Ca II and Hα has dramatically advanced with new electronic detectors. Perhaps most significantly, space-based observations of choromospheric, transition region and coronal emission are now providing a wealth of diagnostic information on the magnetic activity in main sequence stars in both the solar neighborhood and in nearby cluster such as the Hyades and the Pleiades. With this information, a picture has begun to emerge which suggests that, although the main sequence may represent the dullest period of a star's life in terms of *nuclear* evolution, a star's angular momentum, and consequently, it appears, its stellar coronal and chromospheric activity, undergoes dramatic changes during its residence on the main sequence.

Over a decade ago, Stern *et al.* (1981) reported the discovery of X-ray emission from roughly half the stars in the central 5o of the Hyades cluster. These results, obtained with the *Einstein* Observatory (HEAO-2), demonstrated that the typical X-ray luminosity (L_x) of a solar-type G star in the cluster was $\sim 10^{29}$ erg s $^{-1}$, about 100 times that of a "mean" solar corona. Micela *et al.* (1988) continued the *Einstein* studies of the cluster, incorporating more observations outside the cluster center, and deriving detailed X-ray luminosity functions for the main sequence cluster members as a function of color (mass, spectral type). However, both of these studies utilized many indivdual pointings in the Hyades region, and could not hope to cover all known or suspected cluster members. Stern *et al.* 's observational sample was limited to 85 Hyads (48 detections), while the larger Micela *et al.* sample included $\approx$ 121 objects (and detected 66). Once these samples were further divided into sub-samples of differing colors, not to mention single and binary stars, the sample statistics in each bin, while enough to determine gross differences among Hyades stars and the field or other clusters, were not sufficient to provide unambiguous tests for many lines of enquiry.

Because there are now over 400 certain or probable cluster members (see next section), a more complete survey of the cluster in X-rays is clearly warranted. Fortunately, the means for such a study is now at hand in the form of the ROSAT All-Sky Survey (RASS). The RASS constitutes a *complete* X-ray sky survey with a limiting sensitivity in the Hyades region comparable to that of a typical *Einstein* pointing (see below). Thus we now have the opportunity to determine, in an unbiased fashion, the X-ray luminosity function for *all* known or possible members of the cluster established by proper motion, photometry and radial velocity measurements (subject to our known limitations in X-ray sensitivity, especially for the optically fainter stars). In doing so, we hope to establish a true X-ray "base line" study for all cluster members: given the uniqueness of the survey data and the lack of any similar proposed or planned all-sky X-ray survey, the RASS data may also prove to be the only complete X-ray study of the cluster for the next decade or more.

We have previously (Stern *et al.* 1992) provided a preliminary look at the RASS results for the Hyades (with appropriate cautionary remarks). In this paper, we discuss the completed analysis of the RASS data from a 30 x 30 ° region comprising the Hyades cluster (along with a number of smaller regions which incorporate outlying members or possible members), and a database which includes 1163 objects, both Hyades members and stars optically rejected as Hyades members. The inclusion of rejected proper motion motion candidates will, as we shall see, provide an interesting contrast in the frequency of X-ray emission compared to the well-established cluster members. In the next section we discuss the optical catalog of Hyads and rejected Hyads we have compiled from the avaialable literature as well as unpublished material or electronic files kindly provided to us by several Hyades researchers. Following this we describe the RASS, and the the methods of source detection and derivation of upper limits for undetected Hyads, followed by our results and a summary.

3. Optical Catalog

In compiling an optical catalog of the Hyades for comparison with our X-ray survey, many factors must be considered. In particular:

(1) The initial catalog used for cross identifications between the X-ray and optical positions should include certain, probable, and even possible members of the cluster, since, as we shall see, X-ray emission is itself a statitsical indicator of cluster membership.

(2) Unlike our RASS observations, which cover more or less uniformly the entire Hyades region, the various proper motion surveys which provide lists of candidate Hyads generally cover smaller regions, especially for the fainter stars.

(3) Radial velocity meaurements, which, when combined with the proper motion data and multicolor photometry, provide the definitive test of cluster membership, are only available for star with V $\lesssim$ 14. Hence, for many of the stars in the newer proper motion surveys of, e.g., Reid 1992, definitive confirmation of membership through such radial velocity measurements is beywon the reach of current instrumentation.

(4) Membership "probabilities" given in the various proper motion surveys sometimes differ significantly, in some cases for rather "well-known" members: e.g, for the Hyades binary VB22 (HD27130), Hanson (1975) gives a proper motion propbability

of membership of 0! This same object (MClure 1983?) has been used to estimate the distance to the cluster!

Hyades membership may be determined via a combination of proper motions (e.g. van Bueren 1952, van Altena 1969, Hanson 1975, Pels, Oort and Pels Kluyver 1975, Schwan 1991, Reid 1992), photometry (Upgren 1974, Upgren and Weis 1977, Weis, Deluca and Upgren 1979, Weis and Upgren 1982, Stauffer 1982, Weis 1983, Upgren , Weis, and Hanson 1985, Weis and Hanson 1988, Legget and Hawkins 1988, Reid 1993), and radial velocity (Wilson 1948, Kraft 1965, Stefanik and Latham 1985, Griffin *et al.* 1988). Probable members now total $\approx$ 450 or more (Reid 1993), although many of the fainter candidates (V>14) have not been definitively confirmed by radial velocity measurments.

4. Observations

The ROSAT Observatory carried out an all-sky X-ray survey between 30 July 1990 and 25 January 1991. During the all-sky survey the ROSAT X-ray telescope (XRT) scanned the sky once per satellite orbit along great circles containing the north and south ecliptic poles, using the PSPC as the focal plane detector (Trümper *et al.* 1991, Pfeffermann *et al.* 1990). In the plane of the ecliptic, where the Hyades cluster is located, an X-ray source was visible for 2 days in the PSPC 2° FWHM field of view, resulting in typical exposure times of 300 - 400 seconds. Due to its large angular extent (over 40° in RA), scanning of the Hyades cluster occupied more than three weeks during August 1990. During this period, problems with a PSPC gas valve caused a data loss to occur when the very center of the Hyades cluster was scanned: this data was obtained six months later on February 16–17 1991. In March of 1993 these data were finally merged with the rest of the sky survey, allowing, for the first time, a complete analysis of the entire Hyades region.

5. Analysis Techniques

We searched for sources in a 30×30° region of the sky centered roughly at the Hyades cluster center (4^h30^m, +15.0° in J2000) As it turned out, 22 objects in our optical catalog lay outside of this region, so we also searched for sources in $1\times1^\circ$ regions centered at each of these 22 positions. All of the source detection analysis was performed using the EXSAS software developed at MPE. We conducted our analysis in two ways: (1) the entire $30\times30^\circ$ region and outlying 22 smaller areas were searched for sources using the EXSAS LDETECT, MDETECT, amd MAXLIK algorithms (see below), and (2) all objects in our optical catalog were then checked against the ROSAT survey data for detections or upper limits using the EXSAS algorithm COMPUTE/UPPER (see below). Because of the large number of photons contained in the principal $30\times30^\circ$ area of our survey ($\approx$ 1.2 million), we divided this region into 9 overlapping regions of $\approx 11\times11^\circ$ each, for computational reasons. The count rates and likelihoods for sources detected in the overlapping regions of 2 or more fields were compared and, in all cases, the differences were negligible. All source searches were conducted in three pulse-height (energy) bands: PSPC channels 11-181 (Broad), 52-181 (Hard), and 11-41 (Soft). We note that the highest energy channel of the B and H bands is somewhat lower than that usually used by the standard ROSAT processing (SASS). We selected this after determining that the bulk of the Hyades detections contained very little, if any, flux in channels 181-240. This is to be expected for sources with temperatures $\lesssim$1-1.5 keV, as seen in the Hyades (Stern *et al.* 1993). Thus the higher energy channels merely contribute additional background, and therefore reduce the signal-to-noise of our survey.

The LDETECT, MDETECT and MAXLIK techniques are described in Cruddace *et al.* (1988) and Zimmerman *et al.* (1993). Briefly, the LDETECT algorithm assumes nothing about the detector background, and uses a sliding box (typically 3x3 pixels for the survey data) surrounded by a background region having a maximum extent of 5x5 pixels. A simple S/N is calculated for the inner box vs the outer background region, and positions which meet a specific S/N threshold are flagged as possible source locations. Following this, a similar procedure is used, but now the background is taken from a separate "background" map generated by removing all the LDETECT sources' counts from the data. This is called the MDETECT procedure. Again, a list of possible sources which meet a simple S/N criterion is produced. Finally, for each of the possible source locations produced by the LDETECT and MDETECT algorithms, the maximum likelihood procedure described in detail in Cruddace *et al.* (1988) is performed, and sources which yield a likelihood greater than a particular threshold are then accepted into a final source list. The maximum likelihood (ML) procedure is used as the definitive source detection routine, as it computes a likelihood using the known instrumental point response function, hence it will exclude LDETECT and MDETECT sources that are not consistent with point-like objects or that have an anomalous distribution of source counts vs. position. In addition, it is the most sensitive, as it computes the overall likelihhod photon by photon, allowing for the detection of weak, yet statistically significant sources. For our second method of analysis, we used COMPUTE/UPPER, which is an identical algorithm to the MAXLIK algorithm, but with the user supplying a list of possible source locations, e.g. from the Hyades optical catalog.

Usually, the detection threshold for the ROSAT all-sky X-ray survey is chosen such that the probability of a false detection at a given position is 4.5×10^{-5} (ML $\approx$ 10) However, in the case of the Hyades, we lowered this threshold somewhat (to ML=8, P$\approx$ 3.3×10^{-4}). This was done for two reasons: (1) to avoid missing possible sources near threshold, and (2) more importantly, since we have a pre-existing optical catalog of about 10^3 sources, a probability of 4.5×10^{-5} of a spurious source detection is clearly too conservative *when we restrict our position sample only to those positions in the optical catalog.*

6. Results

In Figure 1 we show a composite X-ray image of the entire $30\times30°$ region (Broad band): the individual sources are quite obvious. In the center of the image, a somewhat enhanced source density is attributable to the central Hyades objects. In the upper right can be seen another enhancement due to the Pleiades, and just to the left of the Pleiades two scans of the moon are visible. The Crab is partially visible at the extreme left of the upper portion of the image. Note that this image has been produced by removing a smoothged "background map" and adjusting the count rates in each pixel for varying exposure. Although this removes most of the non-uniformity in the residual background, there is still some evidence of "streaking" in the image due to variations in solar-scattered radiation and other enhancements in the PSPC background.

In Figure 2 we plot the locations of the optical catalog stars and indicate which of those were detected in the Hyades survey. In Figure 3 we plot an HR diagram of the optical catalog, again with the detected sources shown. In Table 1 we show the approximate breakdown and detection rate for the Hyades survey by spectral and luminosity class.

We have studied the distribution between optical and X-ray positions for the Hyades members: in Figure 4 we show the difference (in arcsec) between the optical and the X-ray position for all our Hyades detections, and in Figure 5 we plot a histogram of this distribution for ecliptic latitude, demonstrating that our results are well fit by a gaussian distribution with $\sigma \approx 10$ arcsec. We have provisionally adopted a maximum distance of $60''$ between the optical and X-ray positions as an acceptance criterion for identification.

The typical limiting X-ray sensitivity for our study is ≈ 0.01 ct s^{-1} or $\approx 1.2 \times 10^{-13}$ erg cm^{-2} s^{-1} in the 0.1–2.4 keV band. This corresponds to a limiting L_x of ≈ 1–2×10^{28} erg s^{-1} at the Hyades cluster distance (45 pc), comparable to, but slightly lower than the sensitivity limit for a typical 2000 sec *Einstein* IPC pointing. In Figure 6 we plot the X-ray luminosities vs. B-V color for the detected and undetected Hyads.

Binarity is a key issue for the X-ray luminosity distribution of the Hyades stars. In Figure 7 we plot the the L_x vs B-V color for the Hyades members listed in the paper of Griffin *et al.* (1988): these are most of the Hyads between $6 \lesssim V \lesssim 14$ confirmed by radial velocity measurements. In this plot, we indicate which stars are binaries by either a box with an astrerisk (spectroscopic binary) or a box with a cross (other binary). Note that virtually all of the high-L_x Hyads are binaries. In Figure 8 we plot L_X/L_{bol} vs M_{bol} for the detected Hyads. Finally, in Figure 9 we show a plot of the Hyades PSPC count rates for the ROSAT survey vs. the *Einstein* IPC couint rates from Micela *et al.* (1988) for those sources with detections or upper limits in both investigations. Note that, except for 1 or two objects, most of the Hyads vary by less than a factor of 2 over the $\approx$ decade-long interval between the two studies.

7. Summary

- Approximately 199 (195) detections out of 645 (460) in optical catalog (Reid/LH

Excluded)

- Overall detection rate is $\approx$ 42% excluding Reid/LH, 55% for members with V < 14
- Detection rate for rejected proper motion candidates is low - about 3% or 16 objects.
- Brightest source (excluding V471 Tau - hot WD) is still VB 141
- Anomalously bright sources generally Spect. Binaries
- The X-ray "main sequence" is most apparent for solar-stype stars
- F8-G8 Dwarfs are detected at > 90% rate
- G star mean L_x about the same as *Einstein*
- Several white dwarf detections
- 4 of 4 Hyades Giants detected - 2 are among 10 brightest sources and 2 are near survey limit
- Positions look excellent - Gaussian distributions in Ecliptic Lon and Lat with $\approx 10''$ gaussian width.
- Einstein/ROSAT comparison shows limited scatter except for VB 22 (Einstein Flare) - typically < a factor of two

8. Papers

- "ROSAT All-Sky Survey Observations of the Hyades," R.A. Stern, J.H.M.M. Schmitt, and P. Kahabkha, in preparation, 1993.

9. Foreign Travel

One foreign trip was undertaken by the P.I. from 15 Mar to 24 June 1993 to perform analysis of the ROSAT All-sky-survey data in collaboration with Dr. Jurgen Schmitt of the Max Planck Institut für Extraterrestriche Physik, Garching, Germany.

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TABLE 1

Survey Detections by B-V Color (Reid/LH Excluded)

Sp Type B-V	A-F (-0.1–0.49)	G (0.5–0.79)	K (0.8–1.44)	M (1.45–2.0+)	M (V>15) (No B-V)	Total
Main Sequence	42	52	48	38	9	189
White Dwarfs	2	0	0	0	0	2
Giants	0	0	4	0	0	4
Total Detected	44	52	52	38	9	195
Cataloged	72	57	118	131	82	460
Fraction	0.61	0.91	0.44	0.29	0.11	0.42

Figure Captions

Figure 1. RASS X-ray image (broad band) of $30\times30°$ region centered at 4^h30^m, $+15°$ (J2000).

Figure 2. Positions of stars in optical catalog with detections indicated by boxes.

Figure 3. HR Diagram of optical catalog with detections shown by crosses.

Figure 4. Difference in optical and X-ray positions

Figure 5. Histogram of difference between optical and X-ray positions in ecliptic longitude.

Figure 6. L_x vs B-V for detections (boxes) and upper limts (arrows).

Figure 7. L_x vs B-V for Hyades binaries (*=SB X=other binary). Detections indicated by boxes; arrows indicate upper limits

Figure 8. L_x /L_{bol} vs M_{bol}.

Figure 9. PSPC vs IPC count rates for stars in both Micela *et al.* (1988) study and present RASS results.

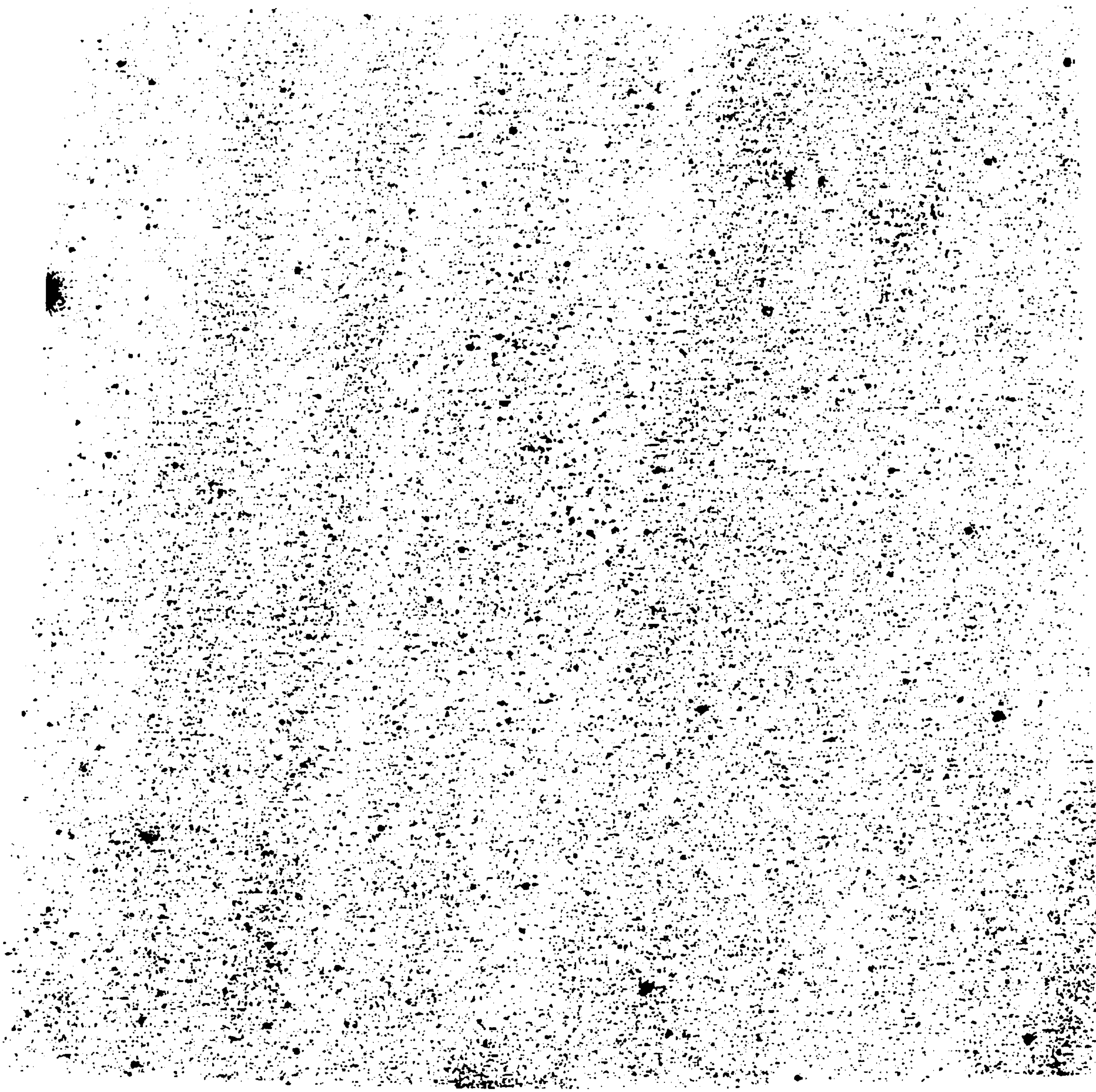


FIG. 1

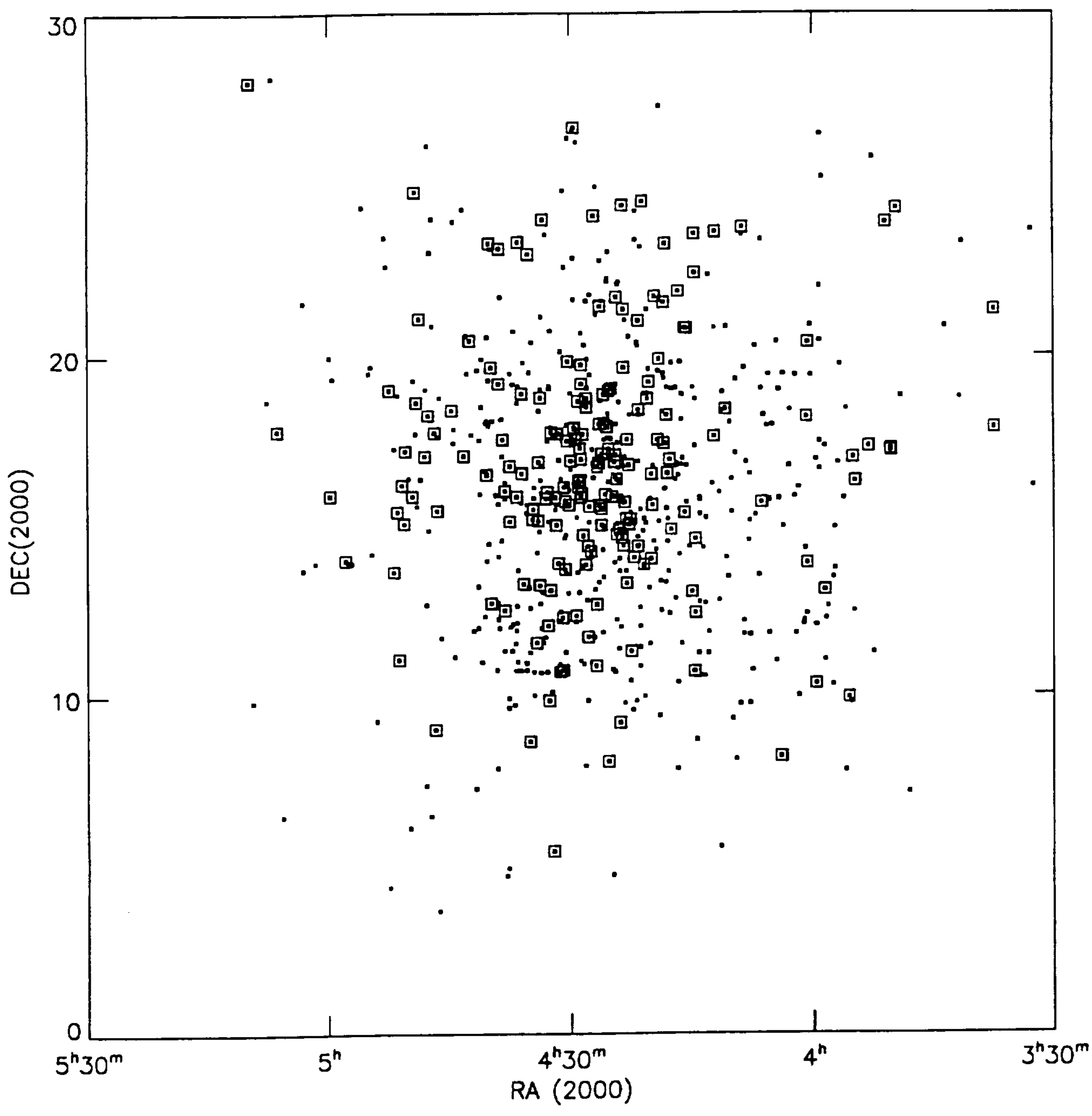
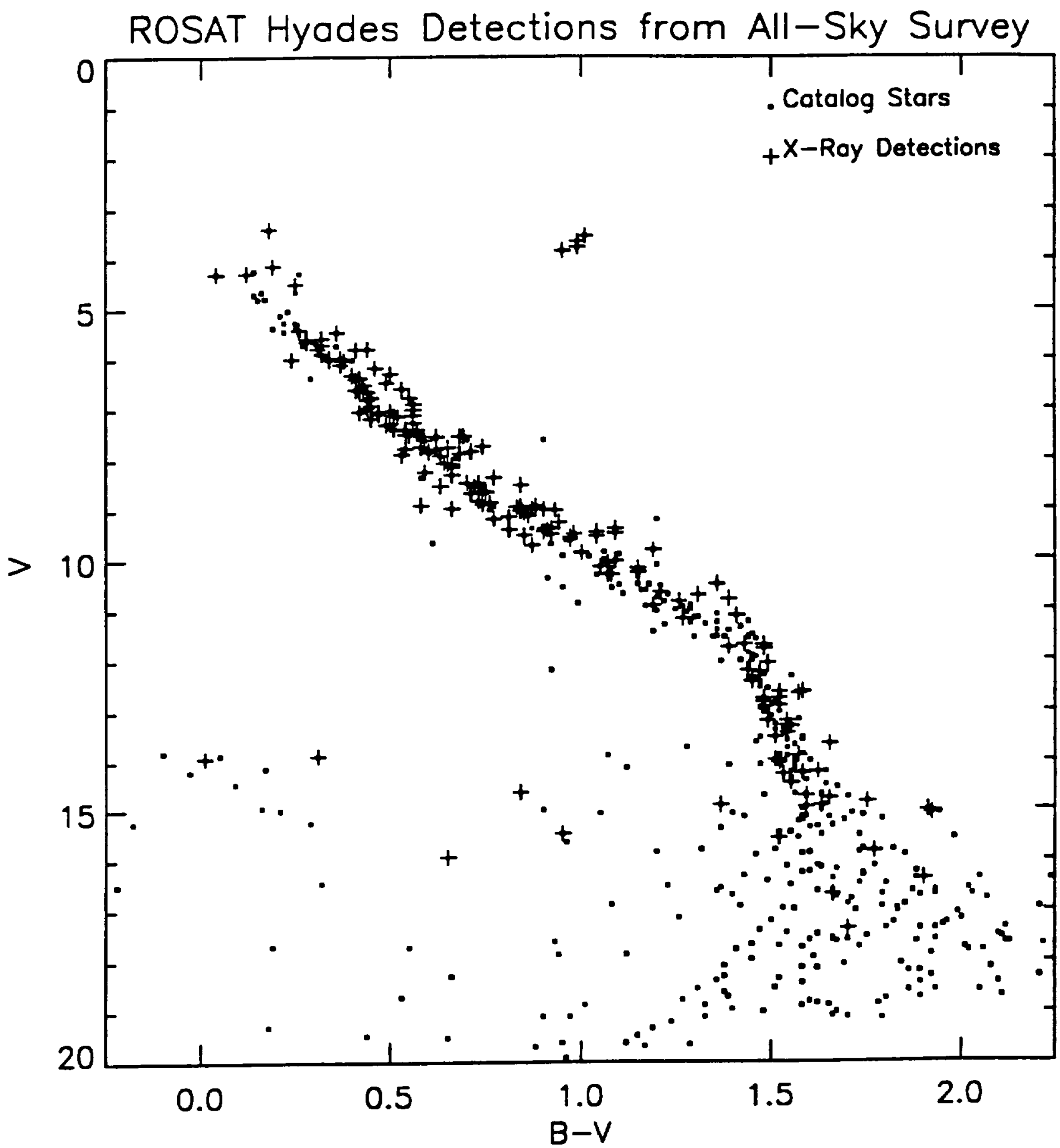


FIG. 2


ROSAT Hyades Detections from All-Sky Survey
Catalog Stars
X-Ray Detections
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5
10
15
20
0.0
0.5
1.0
1.5
2.0
B-V

FIG. 3

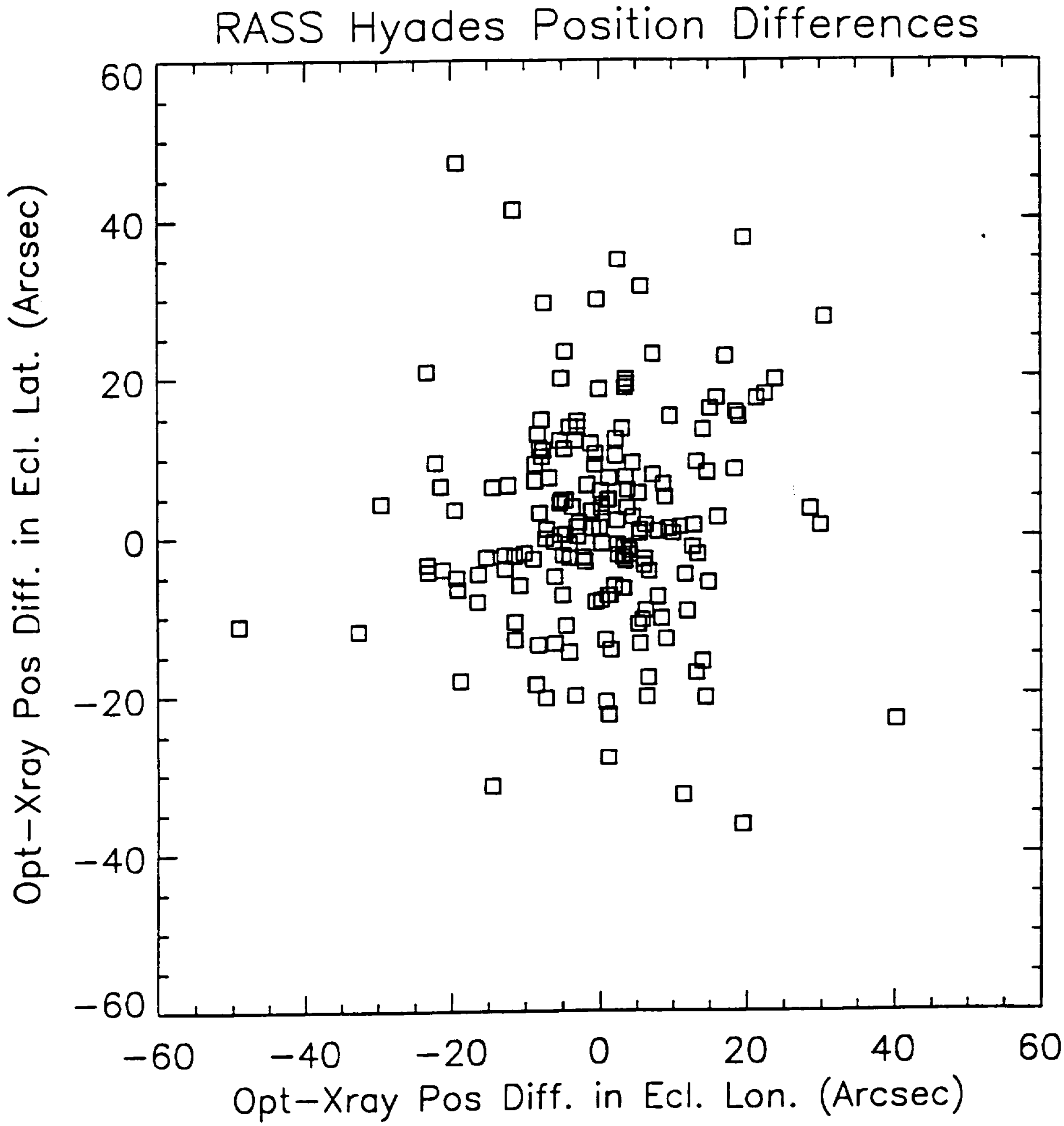

RASS Hyades Position Differences
Opt−Xray Pos Diff. in Ecl. Lat. (Arcsec)
Opt−Xray Pos Diff. in Ecl. Lon. (Arcsec)
60
40
20
0
−20
−40
−60
−60
−40
−20
0
20
40
60

FIG. 4

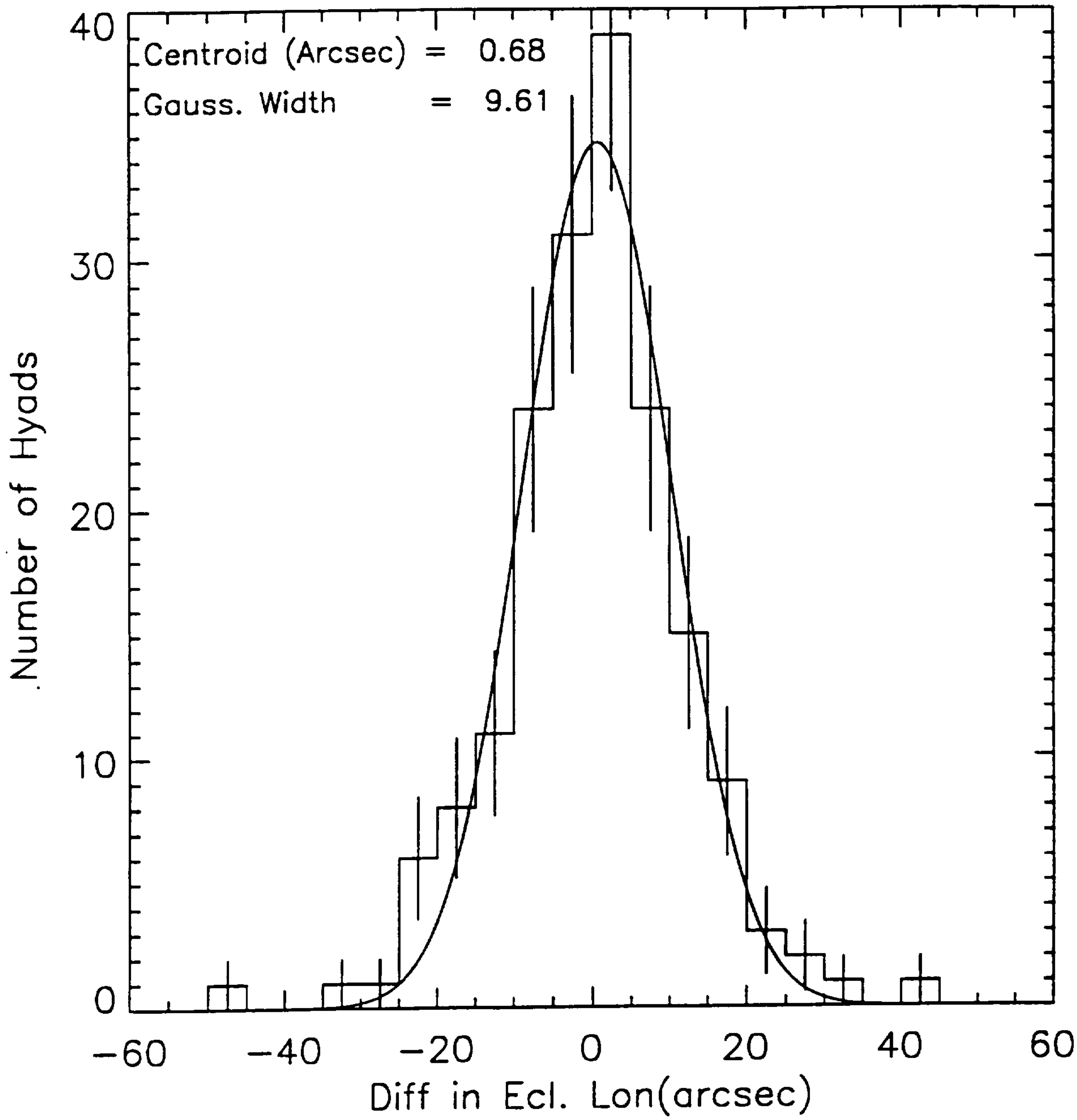

Centroid (Arcsec) = 0.68
Gauss. Width = 9.61
Number of Hyads
Diff in Ecl. Lon(arcsec)
40
30
20
10
0
−60
−40
−20
0
20
40
60

FIG. 5

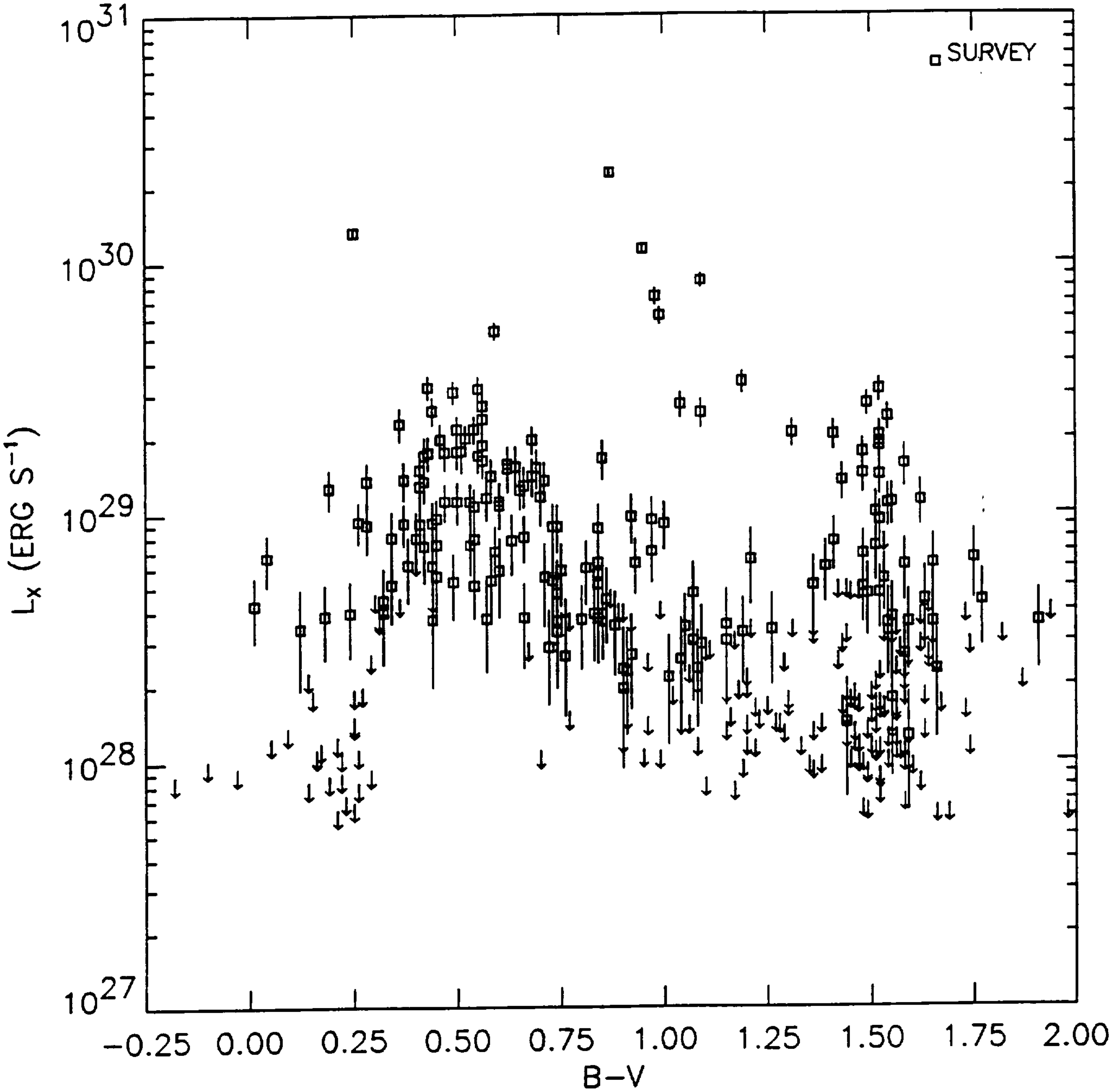
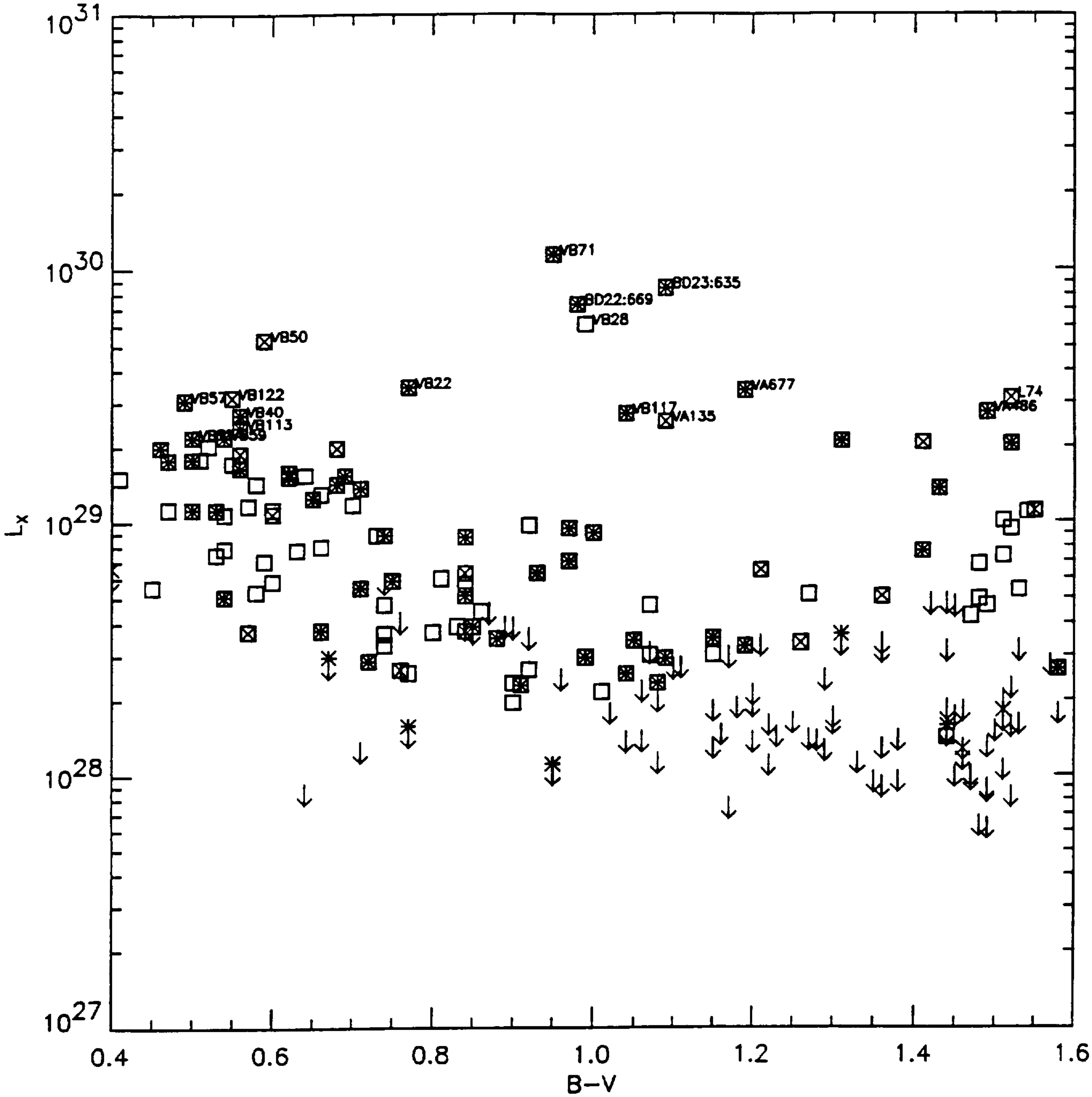

SURVEY
10^{31}
10^{30}
10^{29}
10^{28}
10^{27}
L_x (ERG S^{-1})
−0.25 0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00
B−V

FIG. 6



10^31
10^30
10^29
10^28
10^27
L_x
0.4
0.6
0.8
1.0
1.2
1.4
1.6
B-V
VB71
BD23:635
BD22:669
VB28
VB50
VB22
VA677
L74
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VB40
VB113
VB117
VA135

FIG. 7

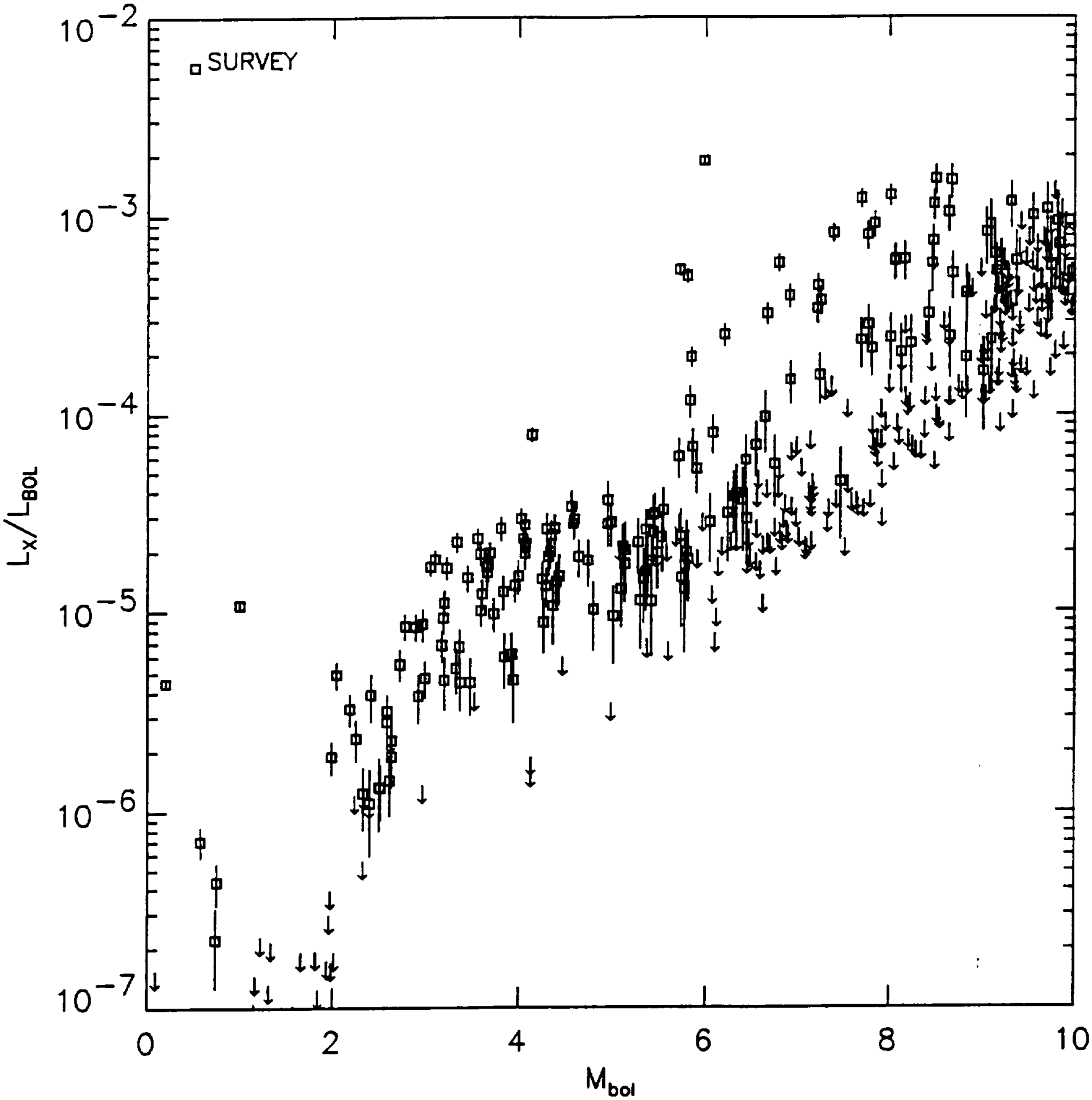
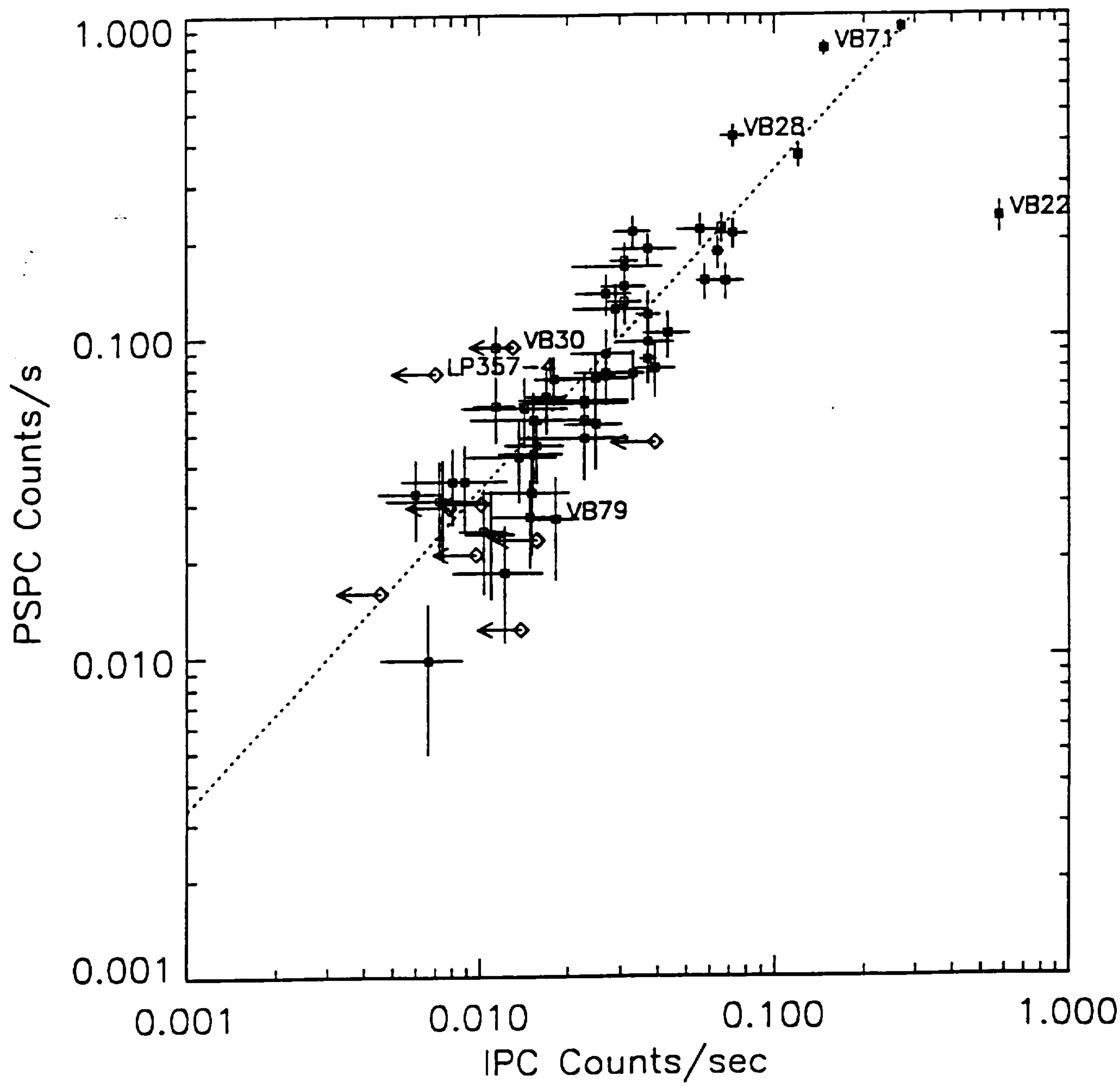


FIG. 8



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VB28
VB22
VB30
LP357-4
VB79
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0.100
0.010
0.001
0.001
0.010
0.100
1.000
PSPC Counts/s
IPC Counts/sec

FIG. 4

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
October 1993

3. REPORT TYPE AND DATES COVERED
Contractor Report

4. TITLE AND SUBTITLE

X-Ray Studies of the Hyades Cluster

5. FUNDING NUMBERS

NAS5-32070

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

CR-189325

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category 89

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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14. SUBJECT TERMS
Hyades cluster, RASS

15. NUMBER OF PAGES
22

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited