CHANDRA X-RAY OBSERVATIONS OF THE YOUNG CLUSTER NGC 6530

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Abstract

We present our initial analysis of a Chandra GTO observation of the very young stellar cluster NGC 6530, associated with the H_{II} region M8 ("Lagoon Nebula"), at a distance of about 1800 pc. A single 60-ksec ACIS-I observation has allowed us to detect 889 point X-ray sources, and we estimate that most of them are indeed cluster members. Therefore, this single Chandra observation has allowed us to select a rich, previously unknown pre-main-sequence population of NGC 6530, enlarging its stellar census by more than a factor of 10. We have also studied the relationships between X-ray emission and basic stellar properties, finding results similar to other star-forming regions (e.g. Orion Nebula). Finally, the new data present a rich variety of X-ray spectra and lightcurves, whose analysis will yield information on the geometrical/thermal structure of the coronae of these stars.

Key words: Stars: coronae – Stars: star-formation regions – objects: NGC 6530

1. Introduction

NGC 6530 is a very young stellar cluster (typical age 1.5 Myr; Sung et al. 2000), located 10′ east of the H_{II} region M8 ("Lagoon Nebula"), a known star-formation region at the center of the Sgr OB1 association. It lies at an estimated distance of 1800±200 pc, very close to the galactic plane (b =−1:20) and near the direction of the galactic center (l =6:03). Both NGC 6530 and M8 are known to contain many OB stars, exciting the surrounding nebula and making it optically bright. Dark absorption lanes are also visible in the same region.

Whenever these characteristics are found, one expects to find also a large number of lower-mass young pre-main-sequence (PMS) stars. These are however elusive, especially at such large distances: members with strong circumstellar activity are selected through Hα surveys, but stars with lower Hα activity are generally missed. In this case, X-ray observations have proven to provide a substantial contribution in the selection of new PMS members. Often, X-ray selected stars constitute a large fraction of the total population of a star-forming region, and this is also the case for NGC 6530: the new Chandra observation we present here shows 889 probable members, to be compared with the 37 members found in Hα studies, and the 41 candidate members from optical variability studies.

2. The Chandra Observation and Data Analysis

NGC 6530 was observed in June 2001 for 60 ksec by Chandra, using ACIS-I on the focal plane. No strong solar flare occurred during the observation, and therefore we had not to reject any time segment. Figure 1 shows the ACIS-I image (4 chips), in the 0.3-8.0 keV band: note that every dark point near image center is a *significant X-ray source.* The source spatial distribution suggests that we have imaged actually most of the cluster. The ACIS-I pointing direction was chosen on the basis of the best previously available X-ray data on NGC 6530, a 10-ksec ROSAT PSPC observation (ROR 900374). The ROSAT data show a few bright sources, and an unresolved emission coincident with the center of NGC 6530, that we now resolve with ACIS-I into hundreds of individual point sources. We could not cover with the same ACIS pointing the optically brightest part of the M8 nebula, the so-called "Hourglass Nebula" containing the very young massive object Herschel 36, where the PSPC also shows the presence of a few bright X-ray sources.

X-ray source detection in the ACIS-I dataset was made using *Pwdetect*, a wavelet-based source-detection method developed at Osservatorio Astronomico di Palermo (updated version of an analogous algorithm working on ROSAT data, Damiani et al. 1997a,b). *Pwdetect* does a multiscale analysis of a Chandra dataset, allowing to detect efficiently X-ray sources ranging from pointlike up to 0.3 arcmin or more. The main features of *Pwdetect* are:

- It works directly on (unbinned !) event lists, and therefore it explores appropriately the entire, richest spatial information content of Chandra observations.
- It uses exposure maps to correct for underexposed regions (ACIS gaps) and to derive accurate source fluxes.
- It computes reference background maps, taking into account the Poisson statistics of background, also in the limit of very low background (per resolution element !), and regardless of the presence of nearby strong point sources.
- It has been extensively tested on large sets of pure-background Chandra simulations, that have also al-

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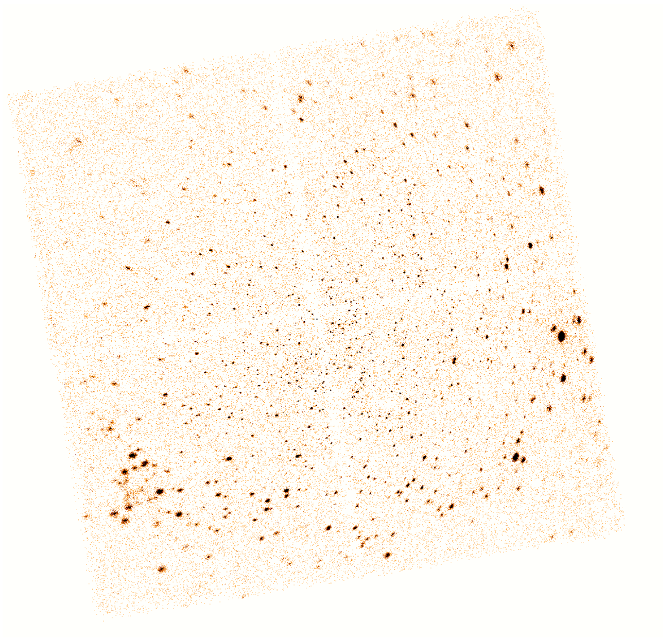

Figure 1. Our GTO Chandra *ACIS-I image of the cluster NGC6530, with exposure time of 60 ksec. 889 point sources are detected.*

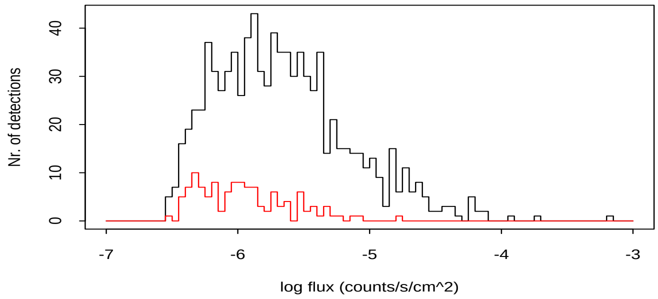

Figure 2. X-ray flux distributions for NGC 6530 (black) and the Galactic Ridge reference ACIS-I observation (red), with similar limiting sensitivity. As is seen, only a little contamination by foreground, non-member sources is expected in the NGC 6530 X-ray source sample.

lowed us to know the thresholds appropriate to have a desired number of spurious detections per field.

The detection threshold was chosen such as to ensure no more than one spurious detection in the ACIS-I field of view. Using *Pwdetect*[1] we have detected **889 point X-ray sources** in NGC 6530. All of the PSPC unresolved emission is now resolved into discrete sources, thanks to the superior spatial resolution of Chandra; this is especially crucial near cluster center, where source crowding is maximum. The sensitivity limit of our observation of NGC 6530, at the cluster distance, is around $\log L_x \sim 29.5$ (ergs/sec).

3. Contamination by Non-Members

Being near the galactic plane, and close to the galactic center, one may suspect a large contamination by back/foreground objects among the 889 detected X-ray sources. We have tried to evaluate such contamination from other ACIS-I observations, as close as possible in exposure time and sky direction. As the best reference observation, we have taken an archived 57.7-ksec ACIS-I observation of the Galactic Ridge (ObsID 1523, PI K.Ebisawa), pointed at (l, b) =(28:27,–0:12), not too far from our pointing, especially in galactic latitude. In this dataset, *Pwdetect* has detected 119 point X-ray sources. In this direction no dark cloud is known, and sources may be detected up to large distances. In the direction of NGC 6530, on the other hand, the dark cloud prevents the detection of background sources, and we therefore expect less than 100 X-ray sources to be non-members of NGC 6530 (i.e. a contamination around 10% or less). Figure 2 shows the detected flux distributions for NGC 6530 and the reference galactic-plane pointing, respectively: it can be seen that most of the contamination occurs at the lowest X-ray fluxes, and even at these fluxes it cannot alter conclusions based on the assumption that basically all NGC 6530 X-ray sources are cluster members.

[1] The Chandra *Pwdetect* is available to the community at `http://www.astropa.unipa.it/progetti_ricerca/PWDetect`

4. Optical Data

We have searched the literature for a catalog of optical photometric data for stars in NGC 6530, and have chosen as a reference the recent compilation by Sung et al. (2000), complete down to V=17, with some stars down to V=18. The region surveyed by Sung et al. overlaps about 80% of our ACIS-I field. Cross-correlating this optical catalog with our X-ray source list we find that 201 (out of 889) X-ray sources have an optical counterpart. On the other hand, there are 374 optical stars, falling in the ACIS-I field but undetected in X-rays, for which we have computed upper limits to the X-ray flux using *Pwdetect*. The optically brightest star in our field, 9 Sgr (O8Iab), is also the brightest X-ray source.

In the near future, we will analyze new BVI photometric data taken with the WFI at the ESO 2.2m telescope, that should reach about V=21.5, assigning thus a counterpart to most, if not all, of our X-ray detected sources. We also plan to conduct extensive spectroscopic campaigns (using the upcoming multi-fiber FLAMES facility at the ESO VLT) to study the nature of these objects in detail.

5. X-Ray Source Properties

To convert count rates to fluxes, we need an X-ray spectral model for our sources. We have defined X-ray color ratios, counting photons in the bands [0.5-1.7 keV], [1.7-2.8 keV], and [2.8-8.0 keV], respectively, and taking (2.5 times the

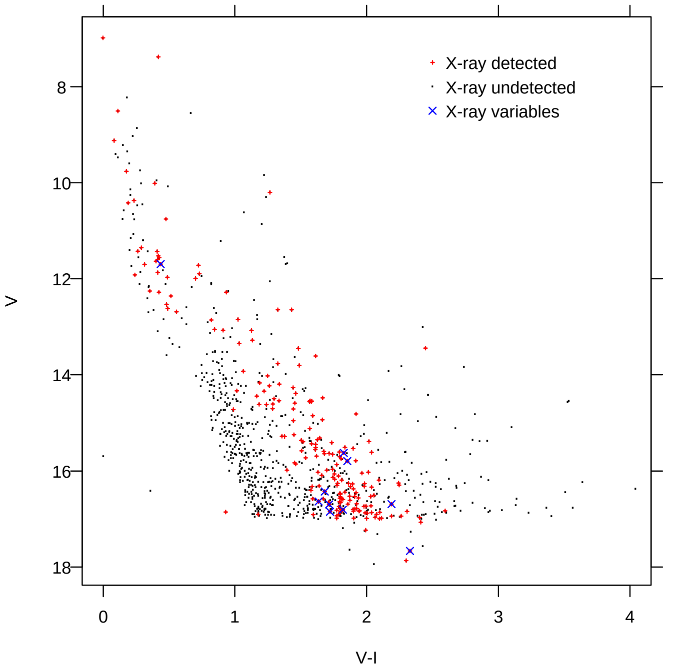

Figure 3. (V,V–I) color-magnitude diagram of NGC 6530, down to V=17. X-ray detected sources are shown in red. Stars with strong X-ray variability are indicated, most of which are of late spectral type.

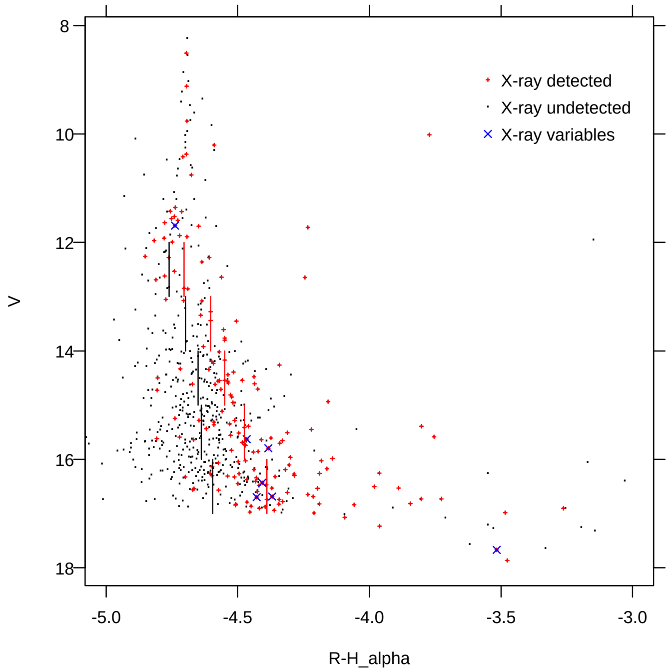

Figure 4. (V,R–Hα) color-magnitude diagram of NGC 6530. Symbols are as in Figure 3. Vertical segments are median values of R–Hα, at 1-mag intervals in V, for X-ray detected (red) and undetected (black) stars, respectively.

log of) their ratio. We have compared these ratios with the prediction of Raymond-Smith single-temperature thermal models, with varying temperatures $\log T$ and absorption N_H. Most sources fall in the temperature range $\log T = 7.2 - 7.8$ (K), and in the absorption range $N_H = 0 - 6 \cdot 10^{21}$ (cm^{-2}), except for a few much softer or much harder sources. The N_H range upper end is in agreement with the optical extinction reported by Sung et al. (2000); accordingly, we have set the lower bound on N_H to the minimum interstellar value for NGC 6530 of $N_H = 1.2 \cdot 10^{21}$ (cm^{-2}). Some sources fall outside the grid, probably since the one-temperature model is inadequate.

Using PIMMS, we have then computed an average conversion factor corresponding to a Raymond spectrum with $\log T = 7.3$ K and $N_H = 1.7 \cdot 10^{21}$ cm^{-2}, a good value to within 10% for most NGC 6530 sources. For the softest source (9 Sgr), and for the two hardest, very absorbed ones, we have computed different, more appropriate conversion factors.

The location of the X-ray detected sample on a (V,V–I) color-magnitude diagram is shown in Figure 3. The detected sources trace very well the locus of a population of very young, contracting PMS stars, at an age of few million years at the distance of NGC 6530 (1800 pc), despite a very significant optical (foreground) contamination. Most X-ray sources with counterpart in the Sung catalog have optical colors corresponding to K-type stars. In Figure 4 we show a (V,R–Hα) color-magnitude diagram, making use of a photometric Hα magnitude (Sung et al. 2000). This figure shows that X-ray detected stars show on average higher Hα emission than undetected stars, but there is no clear-cut separation in R–Hα between the two groups. Many strong-Hα stars are detected in X-rays, but the strongest Hα emitters remain undetected, possibly because of very high circumstellar extinction. Figure 4 shows clearly that our deep X-ray observation selects efficiently PMS stars with low Hα emission, that have escaped all existing Hα surveys.

We have also studied the ratio f_x/f_V versus V–I color (Figure 5), that shows a behaviour found in other star-forming regions (e.g. Orion; Flaccomio et al. 2001, Sciortino et al. 2001), with early-type stars in the $\log f_x/f_V$ range $[-6, -4]$, and late-type stars in the range $[-3, -2]$, with strongly X-ray variable stars at the upper extreme, probably in saturated conditions. Finally, the X-ray luminosity decreases towards later-type stars, although with a large scatter, suggesting a decrease of the maximum (saturated) X-ray luminosity with decreasing bolometric luminosity. X-ray detections without counterpart in our optical catalog cluster around $\log L_x = 30$ (ergs/sec), and should have counterparts fainter than V=17, in agreement with the observed trend.

6. X-Ray Spectra and Lightcurves

We have just started to explore the large amount of ACIS X-ray spectra of NGC 6530 X-ray sources (a selection is shown in Figures 10 and 11). We have 65 sources de-

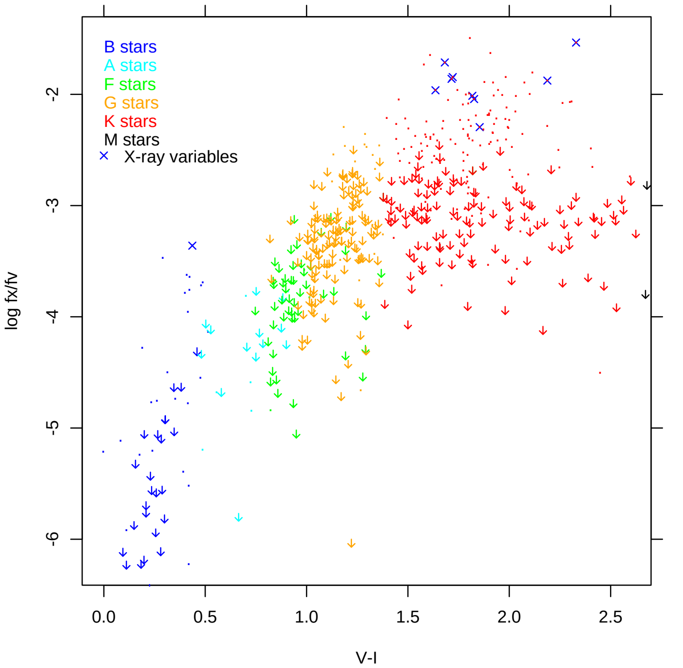

Figure 5. *Ratio f_x/f_V versus V–I color. Stars of various spectral types (from color indexes) are color-coded. Strongly X-ray variable stars (crosses) are mostly late-type stars at the upper extreme of the f_x/f_V range.*

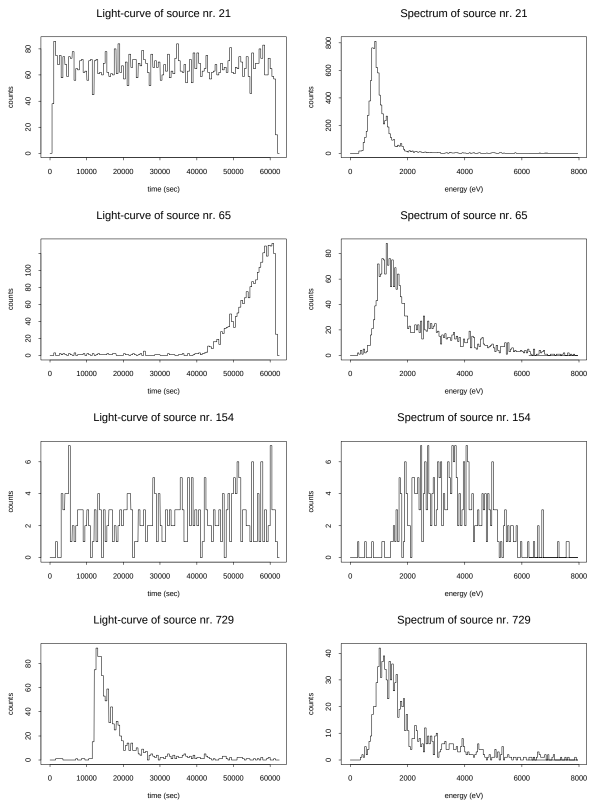

Figure 6. *Examples of ACIS-I lightcurves (left) and spectra (right) of NGC 6530 X-ray sources.*

tected with more than 200 counts, whose spectra can be studied with some detail. Spectra with unusual features (extremely hard or soft) can be identified with even less counts. The softest NGC 6530 X-ray source is the bright O star 9 Sgr. The hardest sources (with no optical counterpart) have very little emission below 1 keV, and are presumably deeply embedded in the cloud; their number is however much less than in Orion (Flaccomio et al. 2001). We plan to perform detailed spectral fittings, that will allow us to study with good statistics the distribution of parameters relative to the thermal structure of these stars' coronae.

We have also plotted in Figure 6 a sample of ACIS-I X-ray lightcurves. These include constant sources (again 9 Sgr), sources with very slow increase/decrease, "bumps" of unclear origin, strong rises, and more classical flares. A study of such a variety of lightcurves will enable us to study the statistics of variability of different kinds, and to obtain information on the geometry of the coronal emitting regions, both in the case of flares, and when rotational modulation is suspected.

7. Conclusions

– We have observed with ACIS-I on Chandra the young cluster NGC 6530, detecting 889 point X-ray sources, most of which are late-type PMS stars belonging to the cluster, down to log $L_x \sim 29.5$ ergs/sec at the distance of NGC 6530.
– Our new Chandra X-ray data have allowed us to enlarge the known PMS population of NGC 6530 by a factor$\sim$20 with respect to previous studies.
– These data imply a substantial revision of completeness estimates for this and other clusters, based uniquely on optical/Hα studies: the cluster IMF (especially at the low-mass end) *cannot* be significantly studied without sensitive X-ray observations.
– Thanks to the superior spatial resolution offered by Chandra, efficient and reliable X-ray selection of PMS stars in young clusters is now possible up to 2 kpc or more, enlarging the volume accessible for these studies by a factor of 10-20 with respect to ROSAT.
– X-ray spectra and lightcurves show a wide variety of shapes; their classification (with good statistics) will yield a substantial body of information on the thermal and geometrical structure of these stars' coronae.

References

Damiani, F., Maggio, A., Micela, G., Sciortino, S. 1997a, ApJ, 483, 350
Damiani, F., Maggio, A., Micela, G., Sciortino, S. 1997b, ApJ, 483, 370
Flaccomio, E., et al. 2001, in preparation
Sciortino, S., et al. 2001, in X-ray Astronomy 2000, eds. R.Giacconi, L.Stella, S.Serio, in press
Sung, H., Chun, M.Y., Bessell, M.S. 2000, AJ, 120, 333