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NGC 2264: a Chandra view

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Abstract. We present results of a *Chandra* ACIS-I observation of the star forming region NGC 2264. We detect 420 sources in the 17'x17' FOV, most of which associated with low mass and/or embedded young members of NGC 2264. In order to derive the IMF of the region, we estimate masses of X-ray selected members using published optical photometry and evolutionary tracks. The IMF we derive after correcting for incompleteness is likely representative of the optically visible part of NGC 2264. Most of the X-ray undetected members are probably X-ray faint low mass Classical T-Tauri stars already identified in the region with H_α and optical variability studies. Uncertainties in the masses estimated through photometry remain for a small fraction of embedded members. Moreover the X-ray data disclose an additional population of deeply embedded members that is not accounted for in the IMF that we have derived.

1. Introduction

Star formation studies have progressed considerably since the first group of contracting protostars was positively identified in the NGC 2264 nebula by Walker (1956, hereafter W56). Many aspects of the star formation process are however still debated (e.g. Lada & Lada 2003) and theories are still in dire need of direction from observations. Star forming regions, where the outcomes of the formation process are more directly observable, are natural targets for such investigations. The Initial Mass Function (IMF) of star forming regions has long been one of the most studied observables of the star formation process (Salpeter, 1955); in particular, differences in the IMFs of regions with different physical characteristics have been sought in order to constrain the physical parameters and the mechanism that leads from molecular clouds to stellar associations and clusters. Such comparative studies (Kroupa, 2002), needing a large sample of well determined IMFs, are not easy because of the difficulties involved in (1) selecting the population of a given star forming region and (2) estimating stellar masses. Representative catalogs of members with masses down to the substellar limit or beyond, are available only for an handful of well studied regions such as the Orion Nebula Cluster (ONC) and Taurus. Completeness down to low masses is important because recent results (e.g. Kroupa 2002) indicate that the IMF is universal at high masses and differences probably appear only at the low mass end.

Because of the much higher luminosity of Pre Main Sequence (PMS) stars in X-rays with respect to older field stars, deep imaging X-ray

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observations of star forming regions are one of the few effective means of selecting unbiased member samples. Other methods, such as observations of strong H_α line emission and IR excesses, proxies of mass accretion and of presence of disks, are effective in selecting Classical T-Tauri stars (CTTS) but not Weak Line T-Tauri stars (WTTS), often a large fraction (depending on age) of the total population.

NGC 2264 is a ~3 Myr old Star Forming Region located at a distance of ~760 pc in the Monoceros. Compared to the ONC and Taurus, NGC 2264 has intermediate stellar density and total population, making it a good target for investigating the dependence of star formation on the environment. Its study is eased by the presence of an optically thick background cloud effectively obscuring unrelated background objects, and by the low and uniform extinction of its foreground population (W56, Rebull et al. 2002). Despite being the first star forming region ever identified as such, the NGC 2264 low mass population is not well characterized. Proper motion studies (Vasilevskis et al., 1965) have been limited to high mass objects; several works have identified CTTS members using disk and accretion indicators (Park et al., 2000; Rebull et al., 2002; Lamm et al., 2004). Lamm et al. (2004, herefter L04) in particular selected a large number of members from broad-band photometry, narrow band H_α data, and optical variability.

Past X-ray observations performed with *ROSAT* (Flaccomio et al., 2000) were useful in identifying the WTTS population, but were not sensitive enough to detect low mass ($M \leq 0.3 M_\odot$) and embedded stars. We present here results from a deep *Chandra* observation of the region. Another similar observation of a field just to the north of the one studied here has been analyzed by Ramírez et al. (2004). The same observation has been used by Sung et al. (2004) to derive the IMF in that region.

2. X-ray Data and Sample Selection

We have obtained a 100Ks long *Chandra* ACIS-I observation of NGC 2264 in October 2002. Using the *PWDetect* wavelet based detection algorithm (Damiani et al. 1997[1]), we detect 420 sources in the 17'x17' field of view (FOV). Details on the data analysis will be presented by Flaccomio et al. (in preparation). Figure 1, shows the run of X-ray luminosity with R-I, showing the well established relation between L_X and PMS stellar luminosity/mass/temperature (Feigelson et al., 1993; Flaccomio et al., 2003a). Here we focus on the contribution of our *Chandra* data to the selection of members and on the consequences for the IMF.

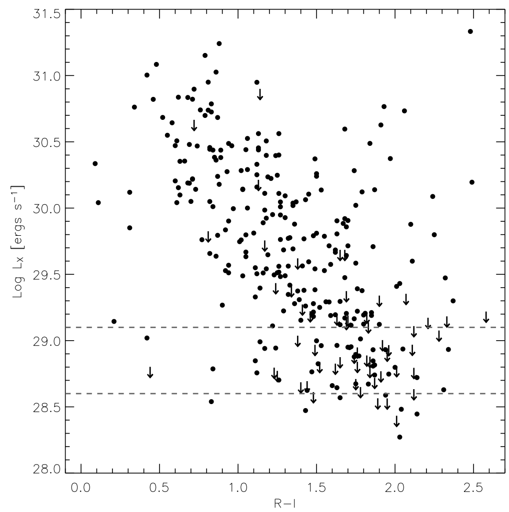

Fig. 1. log L_X vs. R-I. Note the correlation, similar to that of L_X with mass observed e.g. in the ONC (Flaccomio et al., 2003a). Upper limits (arrows) are shown for undetected stars in the H_αV-sample (see text).

We cross-identified our list of X-ray sources with the optical/IR catalogs of Rebull et al. (2002), L04 and 2MASS. 349 sources were uniquely identified with one object, 4 were identified with more than one object, 67 remain unidentified. Because of the higher L_X of PMS stars with respect to field objects, we expect the majority of the detected sources to be associated with members of NGC 2264. This interpretation is supported

[1] See also http://www.astropa.unipa.it/progetti_ricerca/PWDetect

by the I vs. R-I color magnitude diagram (CMD, Fig. 2) clearly showing that X-ray detected stars are preferentially found in the locus where NGC 2264 members with an age of 1-10Myr are expected to lie. Siess et al. (2000) evolutionary models are overlaid on Fig. 2, having been transformed from the L_{bol}, T_{eff} plane to the observational one using tables in Kenyon & Hartmann (1995) and reddened by $A_V = 0.44$, i.e. the median of the A_V values estimated by Rebull et al. (2002) for 61 ACIS sources. Figure 3 shows the K vs. H-K near IR CMD using 2MASS photometry.

In the following we assume that X-ray detected and optically visible stars are cluster members, with the exception of 25 objects that lie, in the optical CMD, outside the photometric *cluster locus*, defined as the region above the $10^{7.1}$yr isochrone *or* to the left of the $0.8 M_\odot$ track (both highlighted in Fig. 2). We will refer to this sample as the *X-sample*. The X-sample comprises 92% (273/298) of the ACIS X-ray sources, i.e. those lying in the *cluster locus*. This fraction can be compared to that of non X-ray detected objects in the cluster locus: 17% (183/1060). Note that 7 X-ray sources are not included in the X-sample because they lie to the right of the $0.1 M_\odot$ track, but they are likely members, either brown dwarfs or of higher mass and absorbed. Figure 2 also indicates the position of stars in a sample of likely members selected with the H_α and variability criteria given by L04 and in the FOV or our ACIS observation. Note that while this sample is richer than that of X-ray sources (350 stars vs. 298), restricting the selections to the cluster locus, as also done by L04 to reduce residual contamination, makes the two samples almost equally populated (278 vs. 273 stars). This indicates that the sample selected from H_α and variability is more contaminated by field objects respect to the purely X-ray selected sample. This larger degree of contamination might persist after selecting stars in the cluster locus. In the following, we will discuss both the X-sample and the union of the X-sample with this new sample restricted to the cluster locus, which we will refer to as the *$XH_\alpha V$-sample*, counting 347 stars.

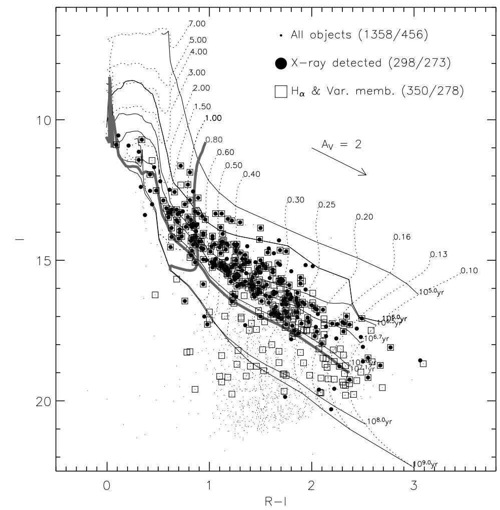

Fig. 2. Optical CMD for X-ray detected/undetected objects in the ACIS FOV. Figures in the legend report the number of objects in the whole diagram and those lying in the *cluster locus*.

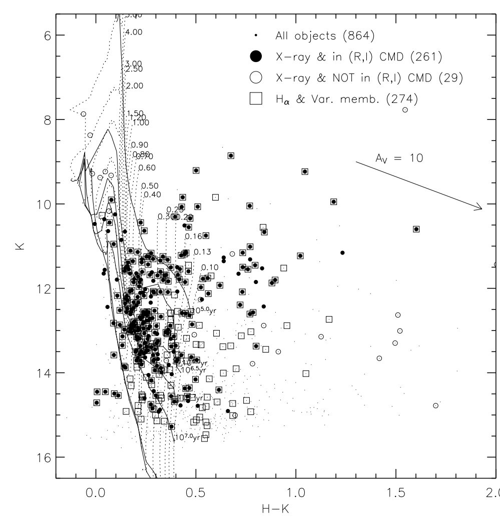

Fig. 3. Near IR CMD. Tracks ans symbols like in the previous panel. X-ray sources not identified with optical objects are indicated by empty circles.

We estimate stellar masses from the CMD in Fig. 2 and the Siess et al. (2000) PMS tracks. This is a potentially error-ridden procedure because (1) we are neglecting the non-photospheric contributions to the photometry due to accretion often observed in PMS stars at the age of NGC 2264, and (2) we are assuming an uniform extinction. Both simplifications are needed because we lack spectral types for the large majority of members: for example, individual estimates of extinction by Rebull et al. (2002) are available for only 61 stars in the $XH_\alpha V$-sample. Our procedure should nonetheless give useful results for two reasons: the R and I magnitudes are actually little affected by non photospheric excesses and reddening is quite uniform for the large majority of NGC 2264 members. This latter conclusion was originally derived by W56 and is confirmed by the J-H vs. H-K color-color diagram (CCD) shown in Fig. 4: the majority of X-ray sources that can also placed in the I vs. R-I diagram (and for which we derive masses), lie close to the theoretical locus. Masses estimated for a few very reddened objects may however be significantly underestimated. Nine X-ray sources have no R and I photometry, but are located within the SDF tracks in the NIR CMD (Fig. 3). We estimate masses for these stars from this latter diagram and add them to the X- and $XH_\alpha V$-samples. Seven of these nine stars are bright objects that were likely saturated in the R and/or I images of L04.

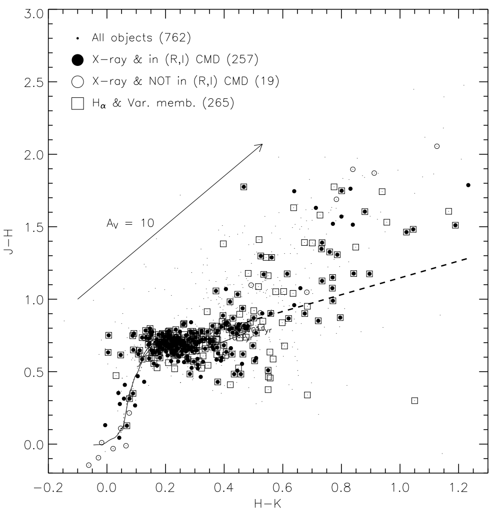

Fig. 4. J-H vs. H-K diagram. The solid line is an isochrone reddened by Av=0.44. The dashed line is the CTTS locus (Meyer et al., 1997).

3. The IMF

Figure 5 shows the mass distribution of the X- and $XH_\alpha V$-samples. Given the L_X-mass relation (cf. Fig. 1) and the sensitivity of our X-ray data, the X-sample is incomplete at low masses. We estimate the completeness fraction vs. mass assuming that the NGC 2264 X-ray luminosity function (XLF) in each mass bin is the same as in the ONC (Getman et al., 2005), where membership and XLFs are well determined. The assumption of similar XLFs is justified by the similar ages of the two regions and by the small dependence of L_X from age at this evolutionary stage (Flaccomio et al., 2003c). We estimate that the minimum detectable L_X with our ACIS data ranges from $10^{28.5}$ to 10^{29} erg/s, depending on the position on the detector. For each mass bin we then determine a range of completeness fractions by taking the values of the ONC XLFs at these two extremes. Dividing the observed X-sample IMF by the completeness fractions we obtain an upper and a lower limit for the *complete* IMF, indicated in Fig. 5 by the hatched area. According to this IMF the total number of stellar mass members in the surveyed area is between 326 and 384, with the X-sample (282 stars) accounting for 73-87% of the total. Note that the completeness corrected X-sample IMF and the $XH_\alpha V$-sample IMF are very similar. The total number of stars in the latter, 356, is only slightly larger than the upper prediction of the completeness corrected X-sample IMF. The disagreement is hardly significant, given uncertainties in the completeness corrections and the small, but finite, degree of field contamination which (see Sect. 2) may be larger in the $XH_\alpha V$-sample than in the X-sample. The overall agreement of the two IMFs indicates that the $XH_\alpha V$-sample accounts for the majority of stellar mass NGC 2264 members. There are indeed reasons to believe that X-ray and H_α/variability selections are complementary:

the former is biased against CTTS, which have lower L_X with respect to WTTS (Flaccomio et al., 2003a,b), the latter against WTTS, these having weak H_α emission and being less variable with respect to CTTS.

Comparing the IMF of NGC 2264 with that of the ONC (Muench et al., 2002), also shown in Fig. 5, we note that NGC 2264 seems to lack stars with $M < 0.3M_\odot$, where our IMF decreases steeply while in the ONC a shallow rise is observed. This might be tentatively related to the different physical conditions of NGC 2264 with respect to the ONC, the effect being similar, but less extreme, to what is observed in the very low density Taurus region.

Finally we compare our IMF with that derived by Sung et al. (2004) for a field in NGC 2264 just to the north of our field and with techniques similar to ours. Sung et al. (2004) give two IMFs, one including only stars selected as "definite" members according to X-ray, H_α and *VRI* photometry and considered as a lower limit to the true IMF, the other including all the "probable" members according to their *VRI* photometry and considered as an upper limit. The former of these two is very similar to the one we derived with a similarly "definite" member sample ($XH_\alpha V$) and confirmed by the completeness corrected X-sample IMF: in particular both show a Salpeter-like slope at high masses, reach a peak at $M = 0.3 - 0.4M_\odot$ and decline at lower masses.

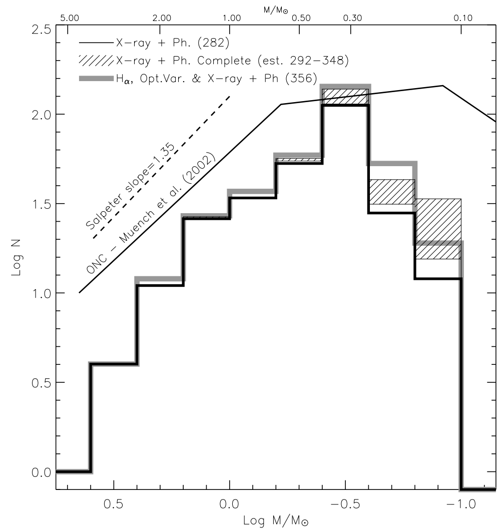

Fig. 5. Solid line: raw IMF of the X-sample. Hatched area: same, corrected for completeness. Gray histogram: IMF of the $XH_\alpha V$-sample. The field stars IMF (Salpeter, 1955) and the ONC IMF (Muench et al., 2002) are shown for comparisons with arbitrary normalization.

4. Un-identified sources

The IMFs presented above may well sample the optically revealed, relatively unabsorbed, population of NGC 2264. Our X-ray data provide however evidence for an additional population of X-ray detected members that are not listed in the optical (106 sources) or NIR (78 sources) catalogs we have used here. These sources must be associated with objects that are intrinsically fainter than the optical/NIR detection limit and/or heavily absorbed: they might be either low mass/embedded NGC 2264 members or extragalactic objects shining through the background molecular cloud. Figure 6 shows the spatial distribution of these X-ray sources. We distinguish optically and IR invisible sources and also indicate sources for which we have indications of high extinction, either from the X-ray spectra (n_H) or from the NIR CCD (Fig. 4): in most cases however such information is not available either because of insufficient statistics in the ACIS spectra or because of lack of NIR data. Figure 6 shows that, while there might be a population of uniformly distributed extragalactic X-ray sources, a considerable fraction of the unidentified sources has the same spatial distribution of cluster members. In particular, note the two concentrations in the south and toward the field center, corresponding to two embedded sub-clusters roughly centered on IRS1 and IRS2 respectively (e.g. Williams & Garland 2002).

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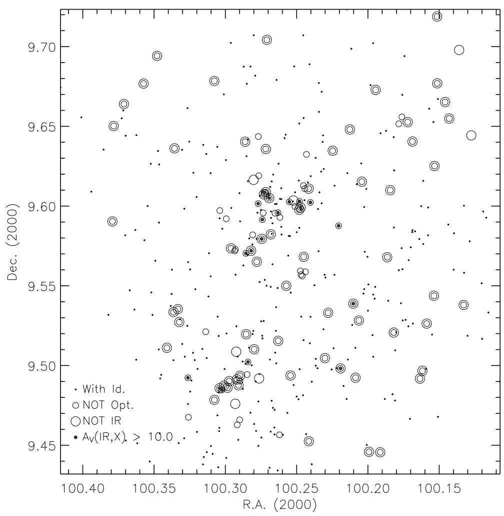

Fig. 6. Spatial distribution of X-ray sources in the ACIS FOV. Circles (see label) refer to sources not identified with optical and/or NIR objects, small dots to other sources.

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