A New Initial Mass Function for NGC 2264 Through Combined X-Ray Observations and BVRI Photometry

By E. FLACCOMIO[1], S. SCIORTINO[1], G. MICELA[1], F. DAMIANI[1], F. FAVATA[2], C. CORBALLY[3], A. TOMANEY[4], F. R. HARNDEN[5], AND J. SCHACHTER[5]

[1]Osservatorio Astronomico di Palermo, Palazzo dei Normanni, 90134 Palermo, Italy

[2]Astrophysics Division - Space Science department of ESA, ESTEC, Postbus 299, NL-2200 AG Noordwijk, The Netherlands

[3]Vatican Observatory Reserch Group, University of Arizona, Tucson AZ 85721, USA

[4]Department of Astronomy, Columbia University, New York NY, USA

[5]Smithsonian Astrophysical Observatory, Cambridge, MA, USA

We present an Initial Mass Function (IMF) of the star forming region (SFR) NGC 2264, obtained by combining the results of our new X-ray and optical surveys of this region. Our X-ray survey is based on an analysis of three ROSAT High Resolution Imager (HRI) observations which were targeted slightly to the northwest of the so-called Cone Nebula and which accumulated a total exposure time of ~ 25 ksec over an interval of ~ 2 years. Using a Wavelet Transform algorithm, we detect 78 X-ray sources with $\log(L_x)$ in the range 30.0 - 31.3 ergs/sec (with source distance taken as that of the NGC 2264 SFR).

For the optical survey, we focused on the central region of the HRI field of view, where the spatial concentration of X-ray sources is highest and the HRI resolves sources confused in previous IPC and PSPC observations. Our CCD photometric observations in the BVRI bands of the Johnson-Cousin system were performed at the Vatican Advanced Technology Telescope (VATT) and yield photometry for 520 stars with $V < 21$.

From the X-ray properties and photometry, we select 92 stars as possibly belonging to the association, 56 of them new. With the addition of these 56 stars to the NGC 2264 SFR, the known population of the surveyed region consist of 126 members. We discuss the derived IMF and the star forming history of NGC 2264.

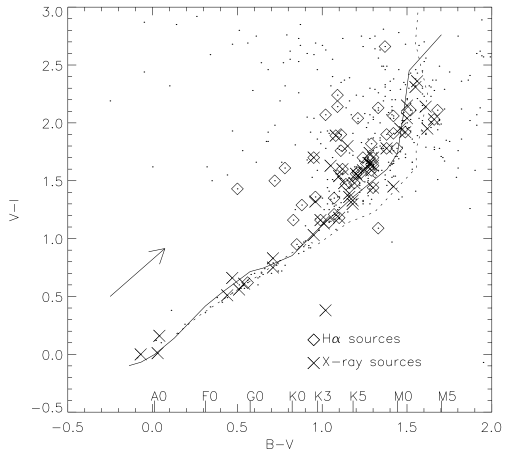
1. Introduction

Placed at about 760 pc (Sung et al., 1997), the star forming region (SFR) NGC 2264, is more distant than other well studied regions with similar characteristics (e.g. Taurus-Auriga or Orion Trapezium). Still it offers a good opportunity of enriching our knowledge of the processes involved in the first stages of star evolution.

In fact, the interpretation of the observational data is greatly eased by two factors: a small *interstellar* visual absorption ($\mathrm{E(B-V)} = 0.06$ mag.; Pérez et al., 1987) for the cluster members and the presence, in the immediate proximity of the region, of an optically thick cloud that effectively obscures background stars.

2. The Observations

We have obtained three distinct HRI observations pointed toward the NGC 2264 southern core – RA, Dec (2000): $6^{\mathrm{h}}41^{\mathrm{m}}07.1^{\mathrm{s}}$, $9^{\circ}26'24.0''$ – for a total exposure time of 24706 seconds. Both the original sequences and their sum have been analyzed with the wavelet transform algorithm described by Damiani et al. (1997), specially adapted for the HRI.



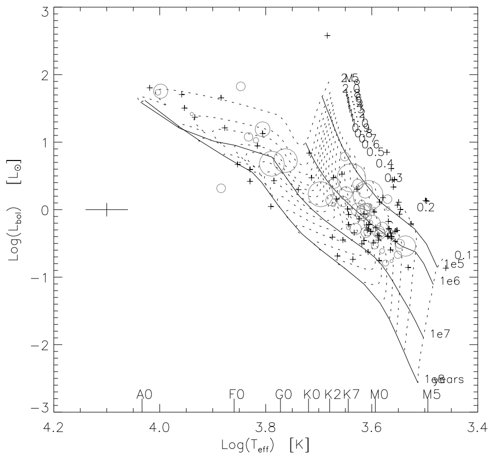


FIGURE 1. [left] Color-color diagram for our photometric data (dots). Positions of our X-ray sources and stars listed as Hα sources in the literature (see text) are marked. Also shown are the main sequence, the giant locus (solid and dotted lines, respectively) and the reddening vector.

FIGURE 2. [right] HR diagram of the X-ray sources unambiguously identified with optical stars (circles) and other NGC 2264 members ("+" symbols). Circle radii are proportional to the maximum X-ray luminosity detected for each source. Theoretical evolutionary tracks and isochrones by D'Antona & Mazzitelli (1994) are also shown.

We have found a total of 78 distinct sources with count-rates ranging between 0.52 and 10.54 cts/ksec. Resulting X-ray luminosities are in the $30.03 < \log L_X < 31.33$ range and were calculated making the following assumptions: a distance of 760pc (Sung et al., 1997); a Raymond-Smith source spectrum with kT $\sim$ 0.75 keV; a standard ratio between $E(B-V)$ and N_H; a visual absorption, $E(B-V)$, equal to the value (0.06 mag.; Pérez et al., 1987) quoted for the 'interstellar' component (i.e. excluding the unknown contribution of any circumstellar material)

We have also observed the central ($\sim 20' \times 20'$) part of the HRI field of view, containing most of the X-ray sources, with the 1.83 meter Vatican Advanced Technology Telescope (VATT) situated on Mount Graham, Arizona. Using the Columbia SpectraSource CCD camera, a 2048^2 pixels detector for a $\sim 11 \times 11$ arcmin^2 field of view, we obtained photometric frames whose analysis has yielded B, V, R_c, I_c photometry for 520 stars with $V \lesssim 21$. We estimate that our sample is complete up to $V \sim 18$. Photometric uncertainties, as given by the residuals of the standard star transformation, were better than 0.05 magnitudes in any given band.

3. Selection of NGC 2264 members

We have compiled a catalog of NGC 2264 members included in our CCD field, using our X-ray and photometric data as well as previous results from the literature. Of the possible counterparts of X-ray sources included in our CCD field, we selected as likely members a total of 52 stars whose identification was unambiguous.

We also selected as members 49 stars whose colors suggest that they are either Classical T-Tauri stars or heavily embedded objects, and thus likely members of the SFR. Fig. 1 shows that most of the redder objects deviate from both the main sequence and the giant loci. As field stars are predominantly Main Sequence (MS) objects, those stars which lie significantly the left of the MS are likely to be Classical T-Tauri stars which are known to show strong excesses in the blue part of their spectra. Moreover, the position of the few stars to the right of the giant locus can be explained by a larger than average reddening. These objects are likely members of the SFR either with a high *circumstellar* absorption or partially embedded in the cloud (note that the cloud directly behind NGC 2264 *totally* obscures background stars, and foreground stars will have small absorptions).

We selected as members those stars that are further from the region bounded by the MS and the giant loci than the photometric uncertainties would allow (i.e. 0.1 mag. in both axes for stars brighter than V=17 with a 2σ confidence).

Our 126 member catalog for NGC 2264 is therefore comprised of: stars brighter than $V = 17$ and selected for their colors using the method just discussed; counterparts of the X-ray sources detected by the HRI; the Hα stars from the catalogues of Herbig (1954), Marcy (1989), Ogura (1984) and Sung et al. (1998); the proper motion stars from Vasilevskis et al. (1965) with membership probabilities greater than 50%.

4. The Initial Mass Function (IMF)

Fig. 2 shows the HR diagram for the selected NGC 2264 members. Masses and ages for individual stars were derived from the D'Antona & Mazzitelli (1994) evolutionary tracks.

In order to construct a meaningful IMF we first estimated the efficiency of the various selection methods we have employed to compile our NGC 2264 member catalog (i.e. detection in X-rays, Hα line emission, color excess and proper motion membership probabilities). For a given stellar mass, the observational biases on the proper motion sample are not correlated with those affecting the other three samples. It follows that, although by themselves biased toward massive stars, in each mass bin members selected for their proper motion constitute a random sample of the whole population, free of biases affecting the other samples.

We can therefore use the proper motion members to derive the (mass dependent) selection efficiency of any of the other samples, e.g., for the X-ray sample we have:

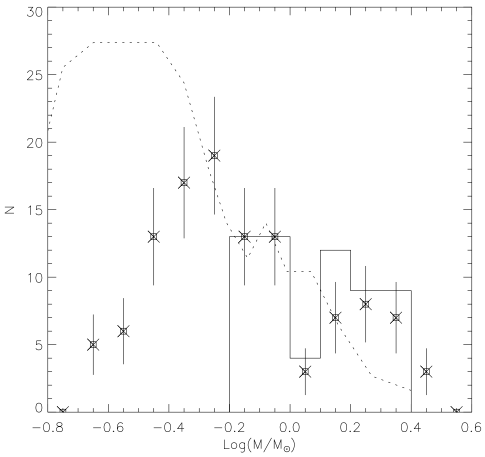
$$\frac{N_X}{N_{total}} = \frac{N_{X\&P.M.}}{N_{P.M.}} \tag{4.1}$$

where N_{total} refers to the total number of members in the field, N_X and $N_{P.M.}$ refer to members detected in X-rays and proper motion surveys, respectively, and $N_{X\&P.M.}$ is the number of proper motion members detected in X-rays.

This calculation has been also performed for the union of the three other samples, in the mass range $0.4 \lesssim \mathrm{Log(M/M_\odot)} \lesssim -0.2$ where the proper motion and composite samples overlap to some degree. We thus estimated the numbers of expected NGC 2264 members in each mass bin. Examining both the estimated IMF and the observed distribution of masses (Fig. 3), we can draw two conclusions: 1) the union of the samples of stars selected as members represents the actual NGC 2264 population reasonably well, and 2) a high mass peak is likely present in the NGC 2264 IMF.

5. Star Formation History

Fig.4 shows the Star Formation Rate for cluster members in two different mass ranges and for the total sample. Both the mass-segregated and total plot show a steep rise in formation activity from the oldest ages to about 1/10 or 1/100 that age; the rate subsequently appears to level off. Given the uncertainties on the position of stars in the



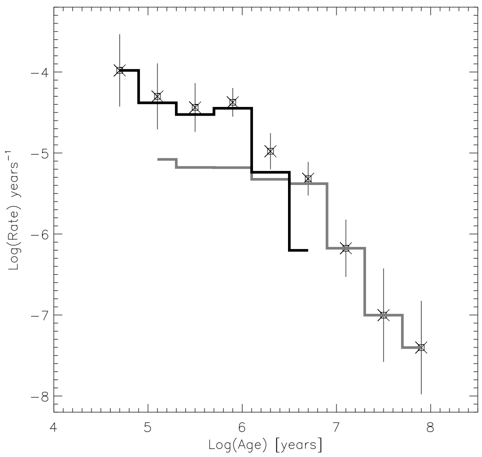


FIGURE 3. [left] Points: mass distribution for the stars selected as members. Error bar are taken as the square root of the number in each mass bin. Solid line histogram: bias corrected IMF. Dotted line: Scalo (1986) IMF with arbitrary normalization.

FIGURE 4. [right] Star Formation Rate vs. Age. Points refer to the whole sample of selected NGC 2264 members and error bars were derived from Poisson statistics. The two histograms, refer to stars more or less massive than $\text{Log}(M/M_\odot) = -0.2$ (gray and black lines, respectively).

HR diagram it can be shown that this apparent trend is compatible with an ongoing and constant star formation activity, which begun a few 10^6 years ago. Moreover there is a hint of sequential star formation as more massive stars seem to be older than less massive ones.

Although interesting, these results remain somewhat tentative due to uncertainties in the dating of stars through the HR diagram and to the expected incompleteness of the known population in the low mass range.

REFERENCES

D'Antona, F. & Mazzitelli, I. 1994, ApJS, 1994, 90, 476.

Damiani, F., Maggio, A., Micela, G., Sciortino, S. 1997, ApJ, 483, 370.

Herbig, G. H. 1954, ApJ, 119, 483

Marcy, G. W. 1980, AJ, 85, 230

Ogura, K. 1984, PASJ, 36, 139

Perez, M. R., The, P. S., & Westerlund, B. E. 1987, PASP, 99, 1050

Sagar, R., Piskunov, A. E., Miakutin, V. I., & Joshi, U. C. 1986, MNRAS, 220, 383

Scalo, J.M. 1986, Fundamentals of Cosmic Physics, Vol 11. (Gordon and Breach)

Sung, H., Bessell, M. S., & Lee, S.-W. 1997, AJ, 114, 2644

Vasilevskis, S., Sanders, W. L., & Balz, A. G. A. 1965, AJ, 70, 797