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Open clusters and stellar associations: recent results of the Italian community

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Abstract. Current research on open clusters and stellar associations in the Galaxy aims to answer key scientific questions at the hearth of stellar physics, such as the universality of the IMF and its shape in the sub-stellar regime, the star and disk evolution from the PMS to the MS phase, the role played by high energy radiation in the YSO (Young Stellar Object) evolution, and its coronal vs. accretion shock origin, the truly coeval origin of young cluster members and its implication on the still controversial speed of the star formation process. The study of clusters with age greater than 1 Gyr is crucial for understanding the evolution and enrichment of Galaxy disk and its implication for the occurrence of similar phenomena in outer galaxies. I will review recent selected results obtained by scientists of the Italian community in this research area.

Key words. Open Cluster and Association – IMF – Star Formation – X-rays

1. Introduction

Thanks to the instrumentation that has been available in the last decade both from space (Chandra, XMM-Newton, Spitzer, HST) and from ground (VLT:FLAMES/ISAAC, WFI, NTT, TNG) the study of open clusters and stellar associations in the Galaxy continues to be a very active research ares as testified by the several tens of papers published in the professional journals each year, by the many dedicated meetings, and by the ample dedicated sections in key international conferences, such as those of the famous "Cool Stars" series.

Current studies are driven and justified by key scientific questions that are at the hearth of stellar physics; among the most relevant are worth mentioning the IMF and its possible dependence on time and position in the Galaxy and its shape in the sub-stellar regime, the star and circumstellar disk evolution from the PMS (pre-main-sequence) to the MS (main sequence) phase, the still unclear role played by high energy radiation in YSO evolution, as well the issue of coronal vs. accretion-shock origin of this radiation, the truly coeval nature of cluster members and its implication on the controversial speed of star formation process. Many Italian scientists are giving first quality contributions to this research field. I will present a personally biased selection of their recent results with special emphasis on those driven or based on photometric observations. In this same volume R. Gratton will instead fo-

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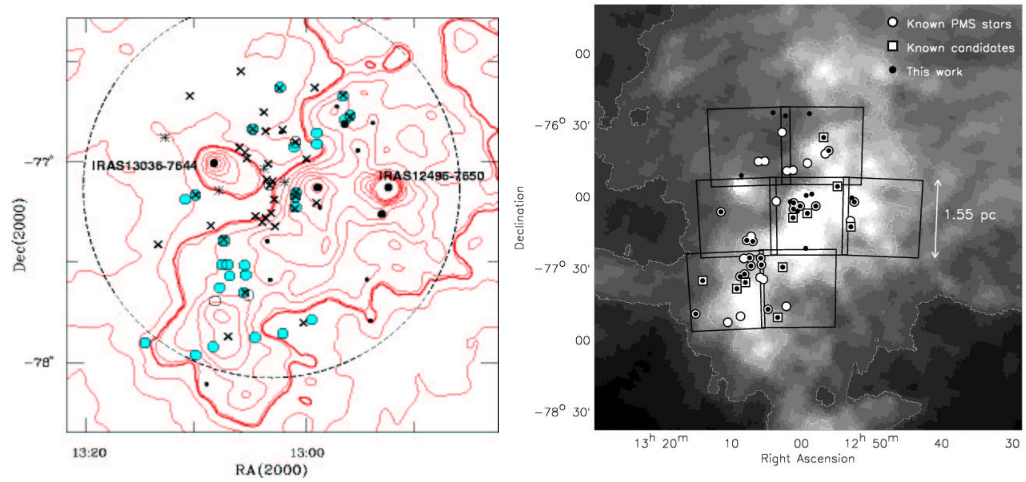

Fig. 1. Left panel: IRAS 100μm map of Cha II. The crosses indicate the X-ray sources, the black, blue and white (colors in the electronic version of figure) filled circles indicate the Class I, Class II and Class III sources, respectively. Right panel: The Cha II WFI survey sky coverage (adapted from Spezzi et al. 2007).

cus on the results obtained by accurate spectroscopic studies of open, as well as globular, clusters.

2. Survey of the Chameleon II SFR

Chameleon II (Cha II) is a 3 Myr old Star Forming Region (SFR) at a distance of 180 pc. Many Cha II YSOs show H_α in emission, a clear sign of ongoing star formation activity. It is a nice region to study the properties of YSOs and of star formation process since the initial conditions are directly observable. The region has been mapped with Spitzer as part of one of the C2D Legacy Surveys

A group of Italian scientists has recently performed a WFI survey (Spezzi et al. 2007) of this region in R, I, z, H_α, m856, m914 (cf. Fig. 1). This survey has allowed to derive accurate optical photometry for the confirmed cloud members (33 PMS stars, 1 BD, and 2 planetary-mass objects). The Cha II population census attained by this survey is nearly (95%) complete down to $M/M_{sun} \sim 0.01$ (for $A_v \sim 0$) or ~ 0.03 (for Av $\sim$ 2) and has allowed to find new 14 PMS and 6 BD candidate members; 50% of the candidates show H_α in emission. Based on the survey results the fraction of sub-

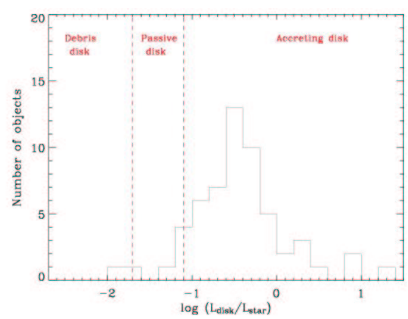

Fig. 2. The distribution of the derived ratio of the disk and star luminosities of Cha II members. The majority of the members are active accretors (adapted from Alcalá et al. 2007).

stellar objects in Cha II ranges from 15% to 19% similar to the fractions obtained for other sparse (T-Tauri) associations, such as Cha I and Taurus, significantly higher than in Lupus (3%) and somewhat smaller than in Orion Nebula Cluster (ONC; 26%±4).

Follow-up spectroscopic observations (Alcalá et al. 2007) have allowed confirming the nature of the candidates thanks to the derived spectral types and henceforth effective temperatures. By adopting recent star+disk

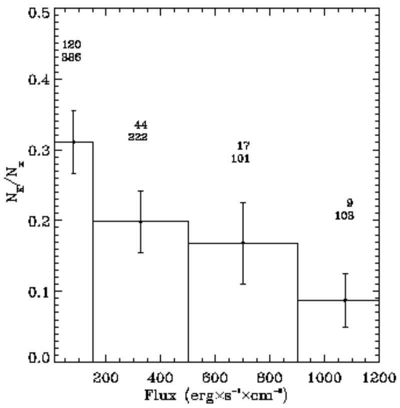

Fig. 3. The distribution of the ratio of the NGC 6611 members with K-band excess – a tracer of circumstellar disk presence – with respect to the size of the overall sample of NGC 6611 members versus the overall UV flux intensity due to the cluster massive stars (adapted from Guarcello et al. 2007).

models (Robitaille et al. 2006) the combined SED of the star+disk systems have been modeled and have allowed deriving separately the luminosities of each star and of its disk. The derived histogram of ratio of disk and star luminosities shown in Fig. 2 confirms that the vast majority of Cha II YSOs are still active accretors. The mass and ages of Cha II members have been computed considering various set of evolutionary tracks, the derived mass and age distributions are similar to those Cha I (Luhman 2004), but the Star Formation Efficiency (SFE) of Cha II is 2-3%, significantly lower than the 7-15% SFE derived for Cha I. The Cha II SFE is in line with values derived for other typical T-Tauri associations.

3. The disk evolution in NGC 6611

NGC 6611 is a relatively nearby (d ~ 2 kpc) and young (age ~ 3 Myr) open cluster characterized by a large number of OB stars (56 earlier than B5) irregularly distributed across the cluster. A recent WFI survey of NGC 6611 together with a X-ray selection of the Class III (WTT) cluster members based on a 100 ks *Chandra* observation has allowed building a complete cluster member sample. The study of this sample has shown (cf. Fig. 3) that the fraction of the members with K-band excess, namely those with conspicuous circumstellar disks, decreases with the increasing of overall intensity of UV radiation emitted by the cluster OB stars (Guarcello et al. 2007) to which lower mass members are exposed. This provides evidence for a fast disk evaporation directly related to the intensity of the UV radiation from the massive stars of NGC 6611.

4. The IMF of NGC 2362

NGC 2362 is a 5 Myr old open cluster, cleared of dust and gas. Hence it is an ideal target for IMF study. NGC 2362 has been observed with *Chandra* for 100 ksec (Damiani et al. 2006). This observation has allowed detecting 387 X-ray sources, 308 of which have been identified with star-like objects using optical and H_α photometric observations. About 88% of the identified sample comprises reliable PMS candidates, and 5-9% of them are active accretors. As a result this survey has largely increased the sample of low-mass, down to 0.4 M_{sun}, cluster members. This new data have allowed deriving the IMFs of Fig. 4 that show a real deficit of low-mass stars, compared to a power law or a log-normal distribution. This result is similar to that found by Wilner & Lada (1991) from optical observations down to a limiting magnitude I < 17.6. Furthermore the survey of Damiani et al. (2006) has shown that the high mass stars are more centrally concentrated than low-mass ones. This is hard to explain in terms of a dynamical evolution process and is interpreted as evidence of primordial mass segregation.

5. X-rays from Class 0 YSOs

Notwithstanding large observational efforts it is still controversial if the Class 0 YSO, i.e. the very early protostars with a lifetime of ~ 10^4 yrs, do emit X-rays. Given the status of the affair I argue that either their emission is weak or rare or it is extremely difficult to find due to the conspicuous amount of intervening absorbing material. While X-rays are quite penetrating –

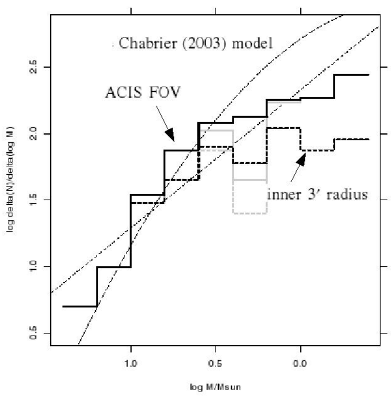

Fig. 4. The IMFs of NGC 2362 members in the entire *Chandra* ACIS FOV (thick solid line) and in the inner 3 radius (thick dashed line). Grey lines are IMFs computed considering a reduced member sample (detail in Damiani et al. 2006) over the whole ACIS FOV (solid), and over the inner part of ACIS FOV (dashed). The thin short-dashed line is a power-law fit, while the thin long-dashed line is the Chabrier (2003) model, arbitrarily normalized (adapted from Damiani et al. 2006).

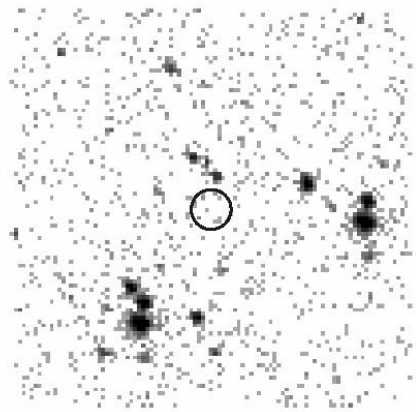

Fig. 5. The staked image obtained by adding ACIS events from six regions of 200 × 200 pixels centered on the position of the 6 known Class 0 sources surveyed for the energy intervals $\Delta E = 0.5-8.0$ keV. The circular region in the center is 5”, corresponding to positional uncertainties of the mm/submm sources. No X-ray source is present within this area indicating that the surveyed Serpens Class 0 YSOs are unlikely to be X-ray sources with intensities just below the detection threshold (adapted from Giardino et al. 2007a).

indeed the absorption at 2 keV and at 2 μm are quite similar – Class 0 sources can be subject to extinction up to 100 magnitudes and even higher preventing the escape of any X-rays. As today the most stringent experiment has been conducted thanks to a 100 ksec *Chandra* observation toward the Serpens SFR (Giardino et al. 2007a). By staking data taken at 6 known Class 0 positions it has been possible to set a bounding upper-limit to Class 0 intrinsic X-ray luminosity at $L_X \sim 4\ 10^{29}$ erg/s (for an assumed emission from an optically thin isothermal plasma with kT = 2.3 keV seen through an absorbing column with $N_H = 4\ 10^{23}$ cm^{-2}). Still this upper limit is a dex higher than the X-ray luminosity of active Sun and further deep observations with current or future X-ray observatories are really needed to set the case.

As matter of fact we do not know when the intense X-ray emission of YSOs develops and when the emitted X-ray emission – that has been shown to locally dominate the ionization level within molecular cloud (cf. Lorenzani et al. (2007) and Fig. 6). – starts to affects the further evolution of star formation process, for example by determining the effectiveness of ambipolar diffusion.

6. The Fe 6.4 keV fluorescent line emission of YSOs

The first detection of a Fe 6.4 keV fluorescent line emission in a YSO has been obtained with Chandra on YLW16A, a Class I YSO in the ρ Oph SFR (Imanishi et al. 2001). The Fe 6.4 keV line was observed during an intense flare. Thanks to the availability of the long COUP data (Getman et al. 2005) it has been possible to collect for 134 Orion YSO spectra of sufficient quality to allow investigating the characteristic of the spectra in vicinity of the Fe XXV 6.7 keV line looking for the presence of the ~ 6.4 keV neutral Fe line. In 7 COUP sources the 6.4 keV line (cf. Fig 7) has been

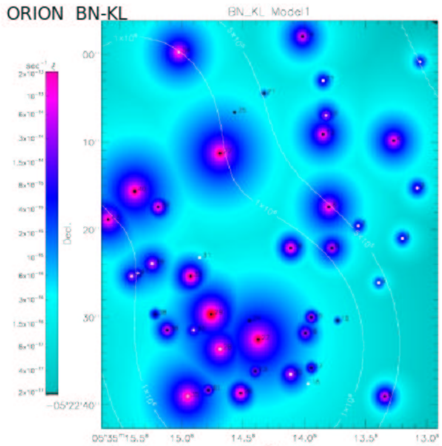

Fig. 6. A two dimensional projection of a model computation of the ionization rate as function of position for the BN cloud core in the Orion Molecular Cloud 1 region. Across the entire core the (color coded) value of ionization rate is higher than the typical value due to cosmic rays (2 10^{-17} s^{-1}) and around each of the embedded X-ray emitting YSOs develops a Röntgen sphere where the X-ray induced ionization rate is several orders of magnitude higher than the background level. (figure courtesy of A. Lorenzani and F. Palla.)

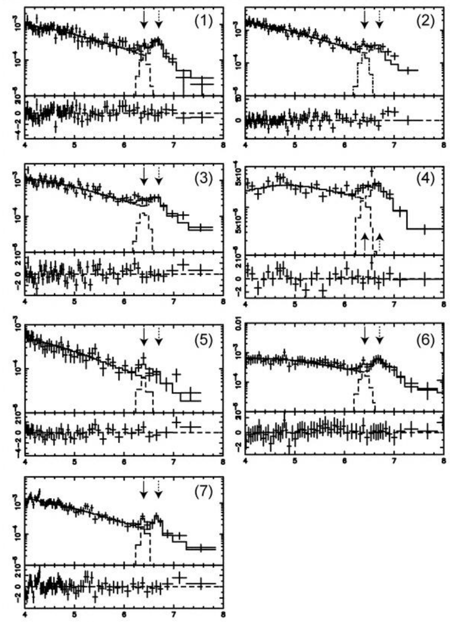

Fig. 7. (Upper panels) Observed spectra (pluses) and best-fit models (solid steps) of the 7 COUP YSOs showing the Fe fluorescent 6.4 keV line. The Fe 6.4 keV line Gaussian component is shown by dashed steps. The 6.4 and 6.7 keV lines are indicated by solid and broken arrows, respectively. Photon energy in keV is on the abscissa, while the ordinate is the spectral intensity as counts s^{-1} keV^{-1}. (Lower panels) Residual to the fit in unit of χ values (adapted from Tusijmoto et al. 2005).

found (Tusijmoto et al. 2005) and the emission has been interpreted, following original suggestion of Imanishi et al. (2001), as originating from the circumstellar neutral disk matter illuminated from the X-ray emitted from the PMS star during the intense flares that have been observed in all those seven sources. A Fe 6.4 keV fluorescent line has also been seen during a relatively short XMM-Newton observation of the Class II YSO Elias 29 without any evidence of concurrent flare emission. In all the above reports none or very limited time resolve spectroscopy has been possible due either to the XMM-Newton too short observation or the *Chandra small* collecting area.

Thanks to *DROXO* (*D*eep *R*ho *O*phiuchi *X*MM-Newton *O*bservation), a XMM-Newton large program (PI: S. Sciortino) aiming to study the properties of X-ray emission of the 1 Myr old ρ Ophiuchi YSOs, it has been possible to perform, for the first time, a time-resolved study of the Fe 6.4 keV fluorescent line emission of Elias 29 (Giardino et al. 2007b). The line intensity is highly variable. It is absent at the beginning of observation, then after a quite typical flare (a factor 8 in intensity with a 6 ksec decay time) it has appeared with a conspicuous equivalent width, EW=250 eV. Subsequentely it continues to be present with EW=150 eV for the remaining 300 ksec (i.e. for 4 days!) of the observation. This behavior challenges the "standard" interpretation of the fluorescent emission being due to photoionizing X-ray photons and suggests an alternative scenario in which the line is collisional

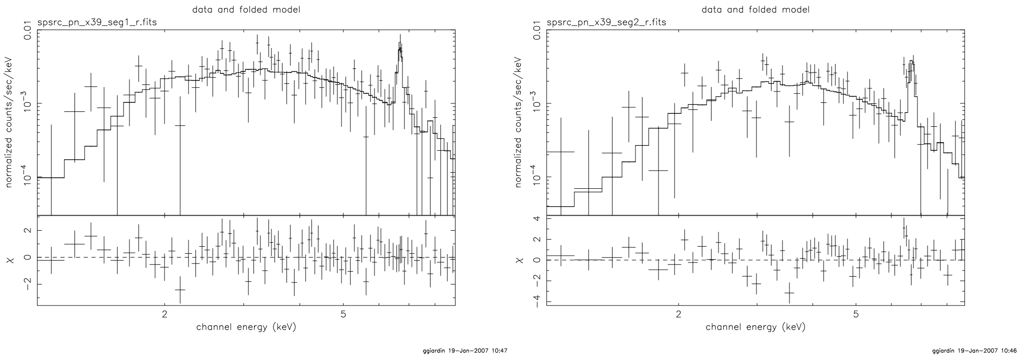

Fig. 8. Spectra and spectral fit to the *DROXO* data of Elias 29 before the flare (left) and after the flare (right). The spectra are very similar in overall shape, intensity, and resulting best fit model parameters. After the flare, however, a significant excess of emission at 6.4 keV is present which is not visible in the data before the flare (adapted from Giardino et al. 2007b).

excited by beams of electrons due to reconnections of magnetic fields occurring in the magnetic funnels connecting the star and its circumstellar disk. The field can be stressed near the corotation radius due to the radial gradient of rotational speed. Those funnels have been predicted by magnetospheric accretion model (e.g. Shu et al. 1997), have been shown to occur in up-to-date MHD simulations of disk-star system (Long et al. 2007,eg.) and have been deduced from the analysis of the flaring structure lengths in a few COUP (Favata et al. 2005) and DROXO (Flaccomio et al. 2007) large flares seen on YSOs.

7. The Lithium Depletion Boundary Test and PMS age

Star formation and early stellar evolution studies require good age determination of stellar clusters and associations. The classical dating methods are the turn-off fitting and the the zero-age main sequence position. Both have their own weakness, the first depends on somewhat uncertain physical inputs, such as convection, mass loss, rotation, the second by the uncertainties in atmosphere models and color transformations.

The Li Depletion Boundary (LDB) test offers a new robust dating method of PMS clusters. With ages of 10-50 Myr they are old enough to be clear of parent molecular cloud material and young enough to ensure that the stellar population represents the final product of star formation. The method relays on the fact that in $\sim$ 20 Myr 0.1−0.4 M_{sun} stars destroy all their initial surface Li, while lower mass stars retain it. Hence the position of the Li boundary is a direct measure of the age of PMS cluster members. This determination is robust since the physics of early PMS Li depletion has little uncertainty. Such an approach has been recently applied to a sample of 6 low-mass high-probability members ($\sim$ 0.1−0.3 M_{sun}) of ONC (Palla et al. 2005, 2007) finding evidence for significant Li depletion (cf. Fig. 9) corresponding to nuclear ages between $\sim$ 15 and 30 Myr. In four cases, there is excellent agreement between the mass and age based on models of Li burning and those derived from the H-R diagram. For the two other stars, the nuclear age is significantly larger than the isochronal one without any clear reason. The observed spread in age shows that the star formation process did not occur into a single fast episode.

A real difficulty of this studies is the selection of PMS clusters in the age range of interest. As today we know just few certain (NGC 2547, Jeffries & Oliveira 2005) or candidate PMS clusters (IC 4665, IC 2602, NGC 2232). Recently a photometric survey of the open cluster IC 4665 aimed to determine

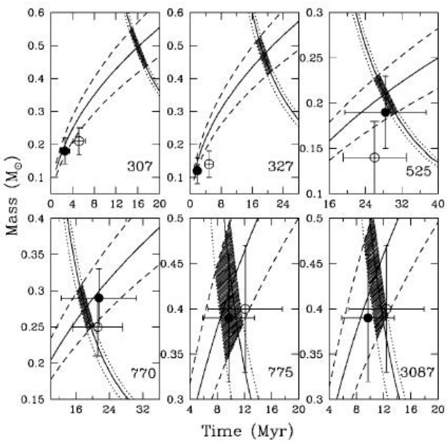

Fig. 9. Mass vs. age plot for the six Orion stars with evidence of Li depletion. Each plot shows the luminosity curve (positive slope) and the Li abundance curve (negative slope) computed for the assumed value of T_{eff}. The uncertainty range in the observed luminosity (0.2 dex, long-dashed line) and in the measured Li abundance (short-dashed line) are also shown. The hatched region bounds the values of stellar mass and age consistent with the observations. The points with error bars give the mass and age from theoretical PMS tracks and isochrones (filled points: Palla & Stahler 1999; open points: Siess et al. 2000).

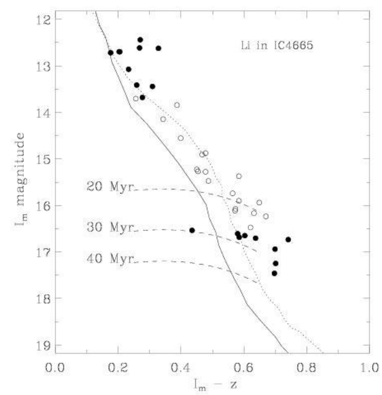

Fig. 10. I_m vs. the I_m-z CMD for IC 4665. Filled symbols indicate members with undepleted Li. Isochrones are shown as dashed lines. The sharp transition between low mass members with and without Li allows determining the cluster age.

its IMF at low mass end has been conducted (de Wit et al. 2006). Further spectroscopic observations taken with VLT have allowed selecting a sample of cluster members (Manzi 2007; Manzi et al. 2007) and to assess the Li abundance for members with I between 12 and 17.5. A clear LDB at I=16.5 is evident from the data (cf. Fig. 10), the deduced age is 28±2 Myr confirming its PMS cluster status, and making IC 4665 the only open cluster for which LDB age is in perfect agreement with nuclear age.

8. The Old Open Cluster King 11

As part of the large BOCCE (Bologna Open Cluster Chemical Evolution, Bragaglia & Tosi 2006) project aiming to perform a systematic study of the Galactic disc through open clusters the Bologna group has recently conducted a deep photometric study of the old cluster King 11 (Tosi, Bragaglia & Cignoni et al. 2007). The study is based on data acquired at the TNG and using the synthetic Color-Magnitude Diagram (CMD) method (cf. Fig. 11) has allowed deriving the best parameters for the King 11 clusters, namely Z = 0.01, age between 3.5 and 4.75 Gyr, distance module between 11.67 and 11.75, and reddening E(B-V) between 1.03 and 1.06.

9. Concluding remarks

The selected recent results obtained by scientists of the Italian community I have reviewed are only a small fraction of a much vast effort at the very frontier of this research field. It is quite remarkable that such a large impact from Italian scientists has been possible notwithstanding the limited amount of resources, both for general and young people support, that have been allocated to this very active field in last few years either from PRIN-MIUR, PRIN-INAF and/or ASI contracts. Indeed a recent analysis has shown how critical it is the lack of perspective for young people even at the post-doctoral fellowship level. We hope for better opportunities in the near future.

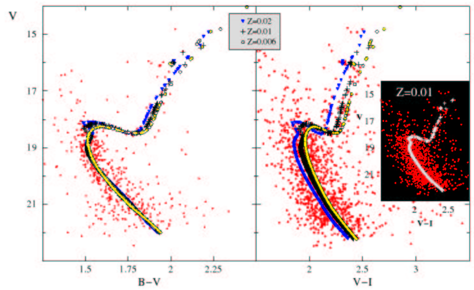

Fig. 11. Determination of the metallicity for King 11: the left panel shows the V, B−V data and the three best solutions (at Z=0.006, 0.01, 0.02) that all reproduce the observed CMD of the cluster central zone, while the right panel shows the same models over-imposed on the V, V−I data (in this case stars from the entire surveyed field are shown). Only the solution at Z=0.01 (shown in the small panel on the right) can well fit at the same time the two different CMDs (adapted from Tosi, Bragaglia & Cignoni et al. 2007).

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