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Galactic open clusters: key tracers of stellar structure and evolution *

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Abstract.
Galactic open clusters are homogeneous samples of stars with approximately the same age and chemical composition but different masses, effective temperatures, rotation rates and magnetic activity. They provide a fundamental tool to test models of stellar structure and evolution and to investigate the formation and chemical evolution of the galactic disk. Recent advances in the study of open clusters are reviewed with emphasis on the determination of lithium and berillium abundances as tracers of internal mixing mechanisms and on the investigation of coronal activity and evolution from the X-ray emission of cluster stars.

Key words. stars – evolution – lithium – berillium – coronae – X-rays

1. Introduction

Open clusters are samples of cospatial and coeval stars with the same, or similar, chemical composition: because of this, they have always played, and continue to play, a fundamental role in astrophysics to test models of stellar structure and evolution as well as to investigate the formation and evolution of the galactic disk. They are key tracers of stellar chromospheric and coronal activity and hence of angular momentum evolution and magnetic field generation by dynamo action. They are also unique stellar dynamical environments where to study mass segregation and its effects on the observed cluster mass function for single and binary stars (see, e.g., the proceedings of the Euroconference *Stellar Clusters and Associations: Convection, Rotation, and Dynamos*, Pallavicini et al. eds., ASP Conf. Series 198, 2000).

Open clusters are numerous in the galactic disk and span a wide range of ages (from a few million years to about 10 Gyr), metallicities ([Fe/H] from about −0.5 to suprasolar), and galactocentric distances. By studying open clusters we can apply key observational tests and derive crucial information for many astrophysical problems such as the structure, evolution and internal mixing of stars, the formation, structure and chemical evolution of the galactic disk, the dynamical evolution of clusters and the determination of the initial

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* based on ground-based observations collected at ESO and TNG and on space observations collected with XMM-*Newton*

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and present day mass functions, the evolution of stellar rotation, dynamo mechanisms and coronal activity, the seach for very-low mass stars and brown dwarfs.

In order to address such a broad range of topics, the study of open clusters requires the combined use of many different techniques, including: 1) *astrometry*, to determine accurate positions, proper motions and cluster membership; ii) *photometry*, to construct C–M diagrams and derive distances, ages, metallicities and reddening from the comparison with theoretical evolutionary tracks; iii) *high-resolution spectroscopy*, to derive radial velocities (for membership and binary orbits), rotation rates, spectroscopic metallicities, abundances of individual elements (Fe, CNO, Li), and to investigate chromospheric activity; iv) *X-ray observations*, to derive information on coronal activity and its dependence on rotation and age, and to identify new low-mass candidate members in young clusters; v) *theory*, to compute theoretical evolutionary tracks and to investigate stellar nucleosynthesis, internal mixing mechanisms, and dynamo models.

As an example of such a broad approach I mention the "WOCS" (WIYN Open Cluster Study) project currently under way in the U.S. by a consortium of astronomical institutes which comprises the University of Wisconsin-Madison, Yale University and NOAO. The WOCS project (Mathieu 2000) is centered on the use of the 3.5m WIYN telescope at Kitt Peak and is focussed on the study of a small well-selected sample of clusters of different ages and metallicities for which comprehensive and definite sets of photometric, spectroscopic and astrometric data are being collected for use as fundamental reference data.

In Europe, and in Italy in particular, the study of open clusters has been limited so far by the lack of suitable multi-object optical spectroscopic facilities, a situation which is now changing with the entering into operation at ESO of the new medium-resolution multi-object spectrograph FLAMES (Pasquini et al. 2002). Most of the observational activity carried out up to now in Italy has been focussed on wide-field imaging and comparison with theoretical evolutionary tracks, and on single-object spectroscopy at ESO and TNG. In addition, extensive observational work has been carried out at X-ray wavelengths using data from *Einstein*, ROSAT, *Chandra* and XMM-*Newton*.

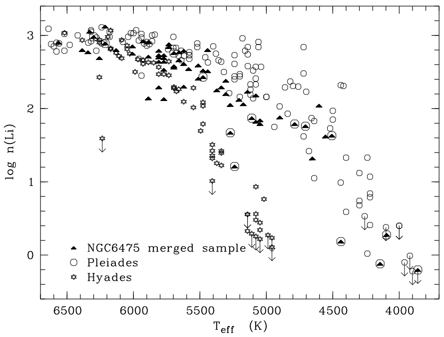


Fig. 1. Li abundances vs. T$_{eff}$ from the age of the Pleiades (~100 Myr) to the age of the Hyades (~600 Myr). From Sestito, Randich, Mermilliod & Pallavicini 2003.

In this paper I will present a summary of recent observational work on open clusters carried out by our group at both optical and X-ray wavelengths. I will focus on the investigation of internal mixing in stars from Li and Be observations, and on the investigation of the evolution of coronal activity from X-ray observations of young clusters. The use of intermediate-age and old clusters to investigate the formation and chemical evolution of the galactic disk is discussed elsewhere in these Proceedings (Bragaglia & Tosi 2003).

2. Lithium abundances

Observations of lithium in stars are important for understanding Big Bang nucleosynthesis, galactic chemical evolution, and stellar structure and evolution. Li is destroyed at relatively low temperatures ($\sim 2.5 \times 10^6$ K) and therefore it is a good

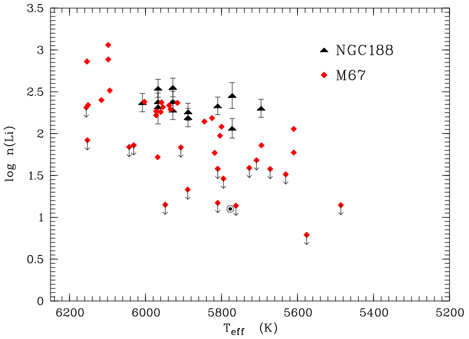


Fig. 2. Li abundance for solar-type stars in the old clusters M 67 and NGC 188. The position of the Sun is also shown. From Randich, Sestito & Pallavicini 2003.

tracer of mixing mechanisms in stellar interiors.

Standard models of stellar evolution (i.e. models that include convection as the only mixing mechanism) predict that Li abundance in stars should be a function of only mass (or equivalently effective temperature), metallicity and age. For solar-type stars, they also predict a large Li depletion in the pre-main sequence (PMS) phase and virtually no Li depletion on the main-sequence (MS). Observations of solar and later-type stars in open clusters of different ages clearly shows that this predictions are at variance with the observations and that Li depletion must depend on additional parameters (e.g. rotation) besides mass, age and chemical composition. As an example, Fig. 1 shows a comparison of Li abundances in the Pleiades (∼100 Myr), NGC 6475 (∼200 Myr) and the Hyades (∼600 Myr) which clearly shows a strong depletion on the MS, contrary to standard models (Sestito et al. 2003). The same figure also shows the large scatter in Li abundances among K stars in the Pleiades (Soderblom et al. 1993), another feature at variance with standard models, possibly due to the different rotational history of different stars in the PMS phase. By the age of the Hyades this scatter has apparently disappeared (Thorburn et al. 1993).

Over the past several years, we have carried out extensive observations of Li in cluster stars using CASPEC at the 3.6m ESO telescope and, more recently, UVES at the VLT and SARG at TNG (Pasquini et al. 1997, 2001; Randich et al. 2000, 2001, 2002, 2003; Sestito et al. 2003). The clusters observed so far cover the full age range from ∼ 30 Myr to ∼7 Gyr and include IC 2602 and IC2391 (∼ 30 Myr), α Persei (∼50 Myr), NGC 6475 (∼200 Myr), Praesepe (∼ 600 Myr), NGC 752, IC 4651, NGC 3680 and NGC 7789 (∼2 Gyr), M 67 (∼5 Gyr) and NGC 188 (∼ 7 Gyr). Other clusters (Blanco 1, NGC 2605, Cr 261) will be observed shortly as part of our guaranteed time on the new multi-object facility FLAMES at the VLT. These observations have allowed us to get a clear understanding of the evolution of Li depletion as a function of mass and age and to put constraints on the various non-standard depletion mechanisms (rotational mixing, diffusion, gravitational waves, mass loss) that have been proposed to explain the observations. An important yet unsolved question is whether or not MS Li depletion depends on metallicity and/or on the abundances of individual elements (e.g. Oxygen) as predicted by standard models. No dependence on metallicity has been convincingly demonstrated so far (e.g. Jeffries 2000): however, accurate metallicity determinations based on high resolution spectra are available only for a few clusters (Gratton 2000) and Li depletion could depend on individual elemental abundances (which affect the opacity and hence the depth of the convective zone) rather than simply on metallicity.

The solar-age solar-metallicity cluster M 67 is characterised by a large dispersion in Li abundances among solar–type stars with similar temperatures (Pasquini et al. 1997, Jones et al. 1999). This spread has not been observed so far in other old open clusters, both younger and older than M 67 (Randich et al. 2000, Randich et al. 2003) while it is present among field stars (e.g. Pasquini et al. 1994): for example, the Sun

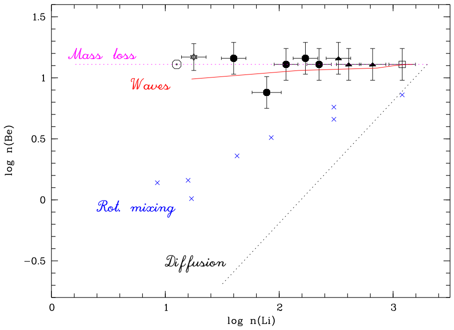


Fig. 3. Be abundances for solar-type stars in M67 and IC 4651 compared with predictions of internal mixing mechanisms. Adapted from Randich, Primas, Pasquini & Pallavicini 2002.

has an observed Li abundance two orders of magnitude lower than young T Tauri stars and the meteorites, and close to the lower envelope of the Li distribution of M 67. Fig. 2 shows the observed distribution of Li abundances in M 67, compared to that of the older cluster NGC 188. While a large scatter is present in M 67, there is no scatter in NGC 188 whose solar-type stars lay all on the upper envelope of the M 67 distribution. The strong Li depletion of many stars in M67 (and of the Sun!) remains completely unexplained.

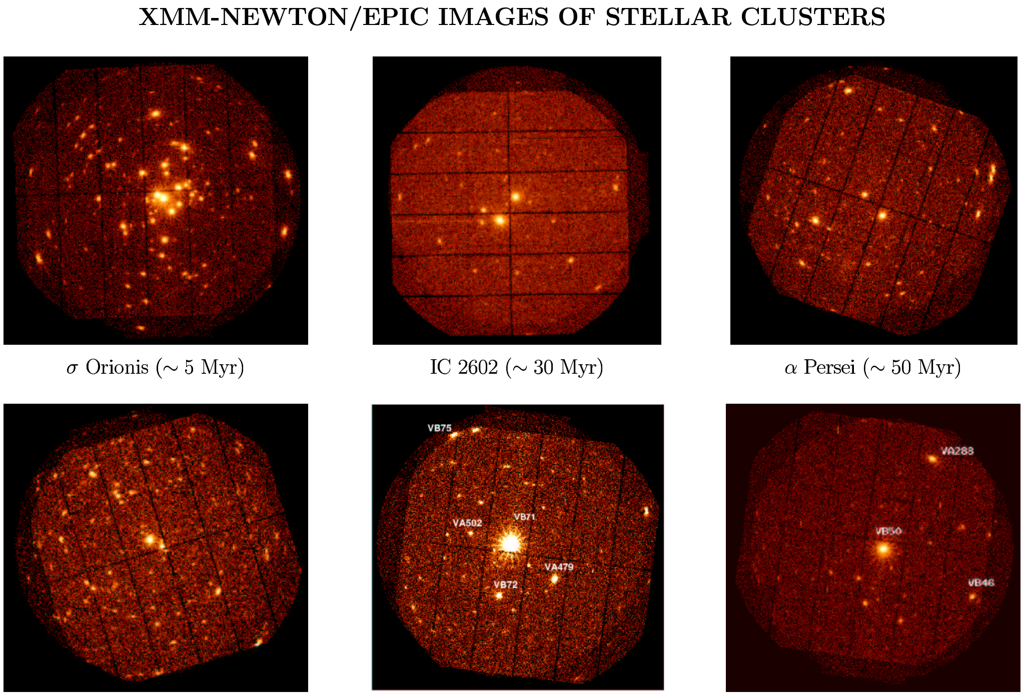
3. Berillium abundances

Another important diagnostics of internal mixing is berillium which is destroyed at temperature of 3.5×10^6 K, i.e. $\sim 1 \times 10^6$ K higher than lithium. Comparison of Li and Be abundances in the same stars provides a tomography of stellar interiors and information on the depth of the mixing process. Be observations have been pioneered by Boesgaard and collaborators using HIRES at Keck as well as smaller telescopes. They have concentrated mainly on F-type field stars and have reported the existence of a correlation between Be and Li abundances that they have interpreted as an indication of rotational mixing in stars (Deliyannis et al. 2000).

We have observed the Be II resonance doublet (λ3130.420 and λ3131.064 Å and the Li I λ6708 Å line in G-type stars of M67 and IC 4651 using UVES at the VLT (Randich et al. 2002). While Li abundances in M67 show a great scatter, there is no indication of Be depletion in either M 67 and IC 4651, which indicates that the mixing is shallow. Moreover, Be and Li abundances are not correlated one with the other (Fig. 3) contrary to the early finding of Deliyannis et al. for field F stars. The absence of a correlation is at variance with the predictions of rotational mixing: a better agreement could be obtained with gravitational wave mixing and/or mass loss, which however cannot explain the lithium data alone. As a matter of fact none of the proposed mechanisms is able to explain simultaneously the Be and Li data. These observations are now being extended to both hotter and cooler stars to further explore this problem and to understand the discrepancy between our results and the Keck/CFHT ones.

4. X-ray observations

X-ray observations of open clusters provide a new powerful way to investigate the evolution of coronal activity in late-type stars and its dependence on magnetic field generation by dynamo action. By observing stars in different clusters it is possible in fact to investigate the dependence of coronal X-ray emission upon rotation and age and to test models of stellar magnetic activity and internal dynamo action. Previous X-ray missions (especially *Einstein* and ROSAT) have allowed a first glipse at the activity-rotation-age relationship in cluster stars (e.g. Randich 2000) and have shown that, on average, coronal activity in late-type stars decreases as a star gets older and rotates more slowly. The details of this relationship, however, are far from being understood thus limiting our ability to model the mechanisms of mag-



σ Orionis (∼ 5 Myr) IC 2602 (∼ 30 Myr) α Persei (∼ 50 Myr)

Praesepe (∼ 600 Myr) Hyades (∼ 600 Myr)

Fig. 4. XMM-*Newton* observations of open clusters of different ages. Adapted from Franciosini, Randich & Pallavicini 2003.

netic field generation and dynamo activity. XMM-*Newton* can provide crucial data on this issue by going much deeper in sensitivity than previous satellites and providing spectral data for the brighter cluster members.

Fig. 4 shows examples of XMM-*Newton* observations of open clusters obtained as part of the GTO program (P.I. R. Pallavicini). The six panels show composite EPIC (MOS+PN) images of young open clusters of different ages, covering the age interval from a few Myr to about 600 Myr (the age of the Hyades). The image on the top left is centered on the hot star σ Orionis which is bright enough for simultaneous high-resolution RGS spectra. The cluster around σ Orionis is extremely young, with an age comparable to that of Star Forming Regions (SFRs). IC 2602 and α Persei are typical examples of clusters intermediate in age between SFRs and the Pleiades (also observed by XMM-*Newton*) and thus provide an important link to understand the evolution of coronal activity from the pre-main sequence phase to the age of the Pleiades (∼100 Myr). Praesepe (lower left panel) is a cluster of the same age as the Hyades, which was reported by ROSAT to be strongly underluminous in X-rays with respect to the latter cluster. The XMM-*Newton* observations have revealed instead a good agreement between this XMM pointing of Praesepe and the Hyades suggesting that Praesepe may result from the merging of two clusters of different ages, with the older one largerly outside of the XMM field of view (Franciosini et al. 2003b). Finally, the two last panels show two different pointings at the Hyades cluster centered, respectively, on the Hyades giant VB 71 (θ^1 Tauri) and on the G dwarf VB 50. The latter two stars are sufficiently bright for simultaneous high-resolution spectra with RGS. Other weaker Hyades members present in the field are also marked in the figure.

In all the above XMM-*Newton* exposures (of about 50 ksec each), a large number of sources (typically between 100 and 200) have been detected, a significant number of which belong to the clusters. Comparison with optical catalogues allows determination of the X-ray luminosity distribution for stars of different spectral types, while comparison of clusters of different ages, and with rotation rates derived from optical observations, allows determination of the evolution of coronal activity with rotation and age. The temperature structure and chemical abundances of the emitting coronae can be determined for the brightest sources from EPIC and RGS spectra. For bright sources detected also by previous X-ray satellites it is possible to investigate time variability over time scales of years, possibly associated to activity cycles. Short term variability (hours) in the form of stellar flares has also been detected during some of the XMM exposures.

The above clusters are all within a distance of a few hundred parsec from the Sun and are much more extended, except the one around σ Orionis, than the XMM-*Newton* FOV. Pointings at other regions of these clusters as well as observations of other clusters of different age will allow a better understanding of the properties of individual clusters and of the evolution of coronal activity with age, including the crucial issue whether a cluster of a given age can be considered as representative of all clusters of the same age (an assumption which has been challanged by recent optical and X-ray observations). Some of these observations, which include clusters intermediate in age between the Pleiades and the Hyades (e.g. M 34) as well as clusters older than the Hyades (e.g. NGC 752), have already been performed or are planned with XMM-*Newton.*

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