X-rays from Open Clusters

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Abstract. The present state of X-ray observations of cool stars in coeval open clusters is reviewed. Concentrating on ROSAT results for solar-type stars, the available observational dataset is summarized along with those details of the evolution of X-ray activity of low mass stars which have been firmly established as a result. Observational questions which are as yet unresolved are then addressed, including the origin of “super-saturation” and whether observations of one cluster can represent the X-ray properties of all clusters at the same age. The role of high spatial resolution X-ray imaging as a tool for identifying cluster members is highlighted and the prospects for future developments with AXAF and XMM are discussed.

1. Introduction

Open clusters are perhaps the best laboratories in which to study the evolution of stellar properties. One might hope they contain stars with a variety of masses, but with roughly the same age, distance and composition. It is not surprising then that much X-ray satellite time has been devoted to the study of open clusters in an attempt to elucidate the roles that rotation, age, composition, binarity, mass and initial conditions play in determining the levels of X-ray emission from a star, if indeed such a deterministic approach is possible.

A major achievement of the Einstein observatory in the 1980s was to show that solar analogues in young clusters could exhibit coronal X-ray activity orders of magnitude greater than our own Sun and that this activity declined as the fast rotating young stars were magnetically braked and lost their initial angular momentum - the age-rotation-activity paradigm (ARAP). A clear goal for the stellar X-ray astronomer would be to describe the history of coronal activity in our own solar system, but as we shall see, this is not yet possible in detail. Furthermore, a comprehensive empirical understanding of X-ray luminosity may provide a route to studying the age distributions of other stellar populations. In the era of the ROSAT satellite the ARAP has been largely confirmed, although various details remain puzzling. Confidence in the ARAP means that X-ray observations can now be used as a tool to find and study the low mass members of open clusters, in circumstances where optical methods of membership selection are difficult or nearly useless.
2. The ROSAT Era

The *Einstein* observatory Imaging Proportional Counter (IPC) showed that stars throughout the H-R diagram emit X-rays, particularly those in close binary systems (RS CVns) and the low mass stars of young open clusters like the Pleiades and Hyades. X-ray luminosity in cool stars with convective envelopes clearly declined with age (Micela et al. 1990), but it had become clear that the primary determinant of X-ray activity was rotation rate. This was interpreted as a natural consequence of the dynamo mechanism whereby the magnetic fields which confine and heat coronae, are amplified by rotation and convection. Indeed, X-ray activity, expressed as the ratio of \( L_X \) to bolometric luminosity (\( L_X/L_{bol} \)), was found to be even better correlated with Rossby number (\( N_R \)), the ratio of rotation period to convective turnover time (Dobson & Radick 1989). The decline of X-ray activity with age was then simply explained in terms of the angular momentum loss (AML) suffered by young, single stars, with tidally locked, short period binary stars remaining a high \( L_X \) polluting factor due to their continued fast rotation. The discovery of spreads in rotation rate among low mass stars at the same age (Stauffer 1991) could then also explain why the X-ray luminosity functions (XLFs) of the Pleiades and Hyades showed some overlap. X-ray emission from higher mass stars was either interpreted as due to a shallow convective layer (early F stars), a lower mass binary companion (A stars) or intrinsic emission from a shocked, radiatively driven wind (early B stars).

The *Einstein* observations of open clusters were only partially satisfactory. The relatively low sensitivity meant that many cluster members (especially K and M stars) were undetected and much of the analysis relied on statistical treatments of upper limits, with consequently uncertain XLFs. Many questions were left hanging, such as: If the ARAP operates in clusters, why is there such a small range of \( L_X \) in the Pleiades where there is more than an order of magnitude spread in rotation rate? What happens to the X-ray activity of stars younger than the Pleiades (\( \sim 100 \) Myr) and older than the Hyades (\( \sim 700 \) Myr)? How much of the spread in X-ray activity at a given age can be attributed to short timescale variability or magnetic activity cycles? Is the activity of one cluster necessarily representative of all clusters at the same age? The launch of *ROSAT* in 1990 offered the opportunity to answer these questions. Its Position Sensitive Proportional Counter (PSPC) and High Resolution Imager (HRI) had greater sensitivity, higher spatial resolution and in the case of the PSPC, more spectral resolution than the IPC.

Table 1 is an update from the reviews of Caillault (1996) and Randich (1997), which summarizes the *ROSAT* dataset on clusters (older than 10 Myr). References to published results are given or if unpublished, the PI on the observation is indicated. Ages and distances are adopted from the Lyngå (1987) catalogue and should be treated with caution! There are now deep, reasonably consistently calibrated soft X-ray observations of more than 25 open clusters. This massive database has answered most of the questions posed by *Einstein*, but yielded a number of new mysteries. In particular the XLFs of F G and K stars are now well determined, with few upper limits, in several open clusters at ages from 30 Myr to 600 Myr.
Table 1. Open clusters observed with *ROSAT* (ages and distances from Lyngå 1987).

| Cluster   | Log Age (yr) | Distance (pc) | ROSAT Instrument | References |
|-----------|--------------|---------------|------------------|------------|
| IC 2602   | 7.00         | 155           | PSPC (R)         | Randich et al. 1995, A&A, 300, 134 |
| NGC 2232  | 7.35         | 400           | HRI (P)          | Prosser    |
| Coll 140  | 7.35         | 300           | HRI (P)          | Prosser; PI Theissen |
| IC 2391   | 7.56         | 140           | PSPC (P)         | Patten & Simon 1993, ApJ, 415, L123 + |
|           |              |               |                  | Patten & Simon 1996, ApJS, 106, 489 |
| IC 4665   | 7.56         | 430           | HRI (P)          | Giampapa et al. 1998, ApJ, 501, 624 |
| NGC 2451  | 7.56         | 220           | HRI (P)          | Schmitt et al. 1996, ApJS, 102, 75 |
| Blanco 1  | 7.70         | 190           | HRI (P)          | Schmitt et al. 1993, A&A, 277, 114 |
| Alpha Per | 7.71         | 170           | PSPC (R)         | Randich et al. 1996, A&A, 305, 785 |
|           |              |               | Patten & Simon 1996, ApJS, 106, 489 |
| NGC 2547  | 7.76         | 400           | HRI (P)          | Prosser et al. 1996, AJ, 112, 1570 |
| NGC 2422  | 7.89         | 480           | PSPC/HRI         | Barbera et al. 1996, CSS9, p.355 |
| Pleiades  | 7.89         | 125           | PSPC (P)         | Stauffer et al. 1994, ApJS, 91, 625 + |
|           |              |               |                  | Gagné et al. 1995, ApJ, 500, 217 |
|           |              |               |                  | Miletta et al. 1996, A&A, 312, 818 |
| Stock 2   | 8.00         | 320           | HRI (P)          | Prosser    |
| NGC 2516  | 8.03         | 440           | PSPC (P)         | Dachs & Hummel 1996, A&A, 305, 785 |
|           |              |               | PSPC (P)         | Jeffries et al. 1997, MNRAS, 272, 350 |
|           |              |               |                  | Miletta et al. 1996, A&A, 277, 114 |
| NGC 1039  | 8.29         | 440           | HRI (P)          | Prosser et al. 1995, AJ, 112, 1229 |
| NGC 6475  | 8.35         | 240           | PSPC (P)         | Prosser et al. 1995, AJ, 112, 1229 |
| Praesepe  | 8.82         | 180           | PSPC (R)         | Randich & Schmitt 1995, A&A, 298, 115 + |
| NGC 6940  | 9.04         | 800           | PSPC (P)         | Barrado et al. 1998, ApJ in press |
| NGC 752   | 9.04         | 400           | PSPC (P)         | Belloni & Verbunt 1996, A&A, 305, 680 |
| NGC 3680  | 9.26         | 800           | HRI (P)          | Belloni & Verbunt 1996, A&A, 305, 680 |
| IC 4651   | 9.38         | 710           | PSPC (P)         | Belloni et al. 1996, ApJS, 106, 489 |
| M67       | 9.60         | 720           | PSPC (P)         | Belloni et al. 1996, ApJS, 106, 489 |
| NGC 188   | 9.70         | 1550          | PSPC (P)         | Belloni 1997, MemSAIt, 68, 993 |

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*P - pointed observation, R - raster scan observation, S - all-sky survey observation*
2.1. The Age-Rotation-Activity Paradigm

At the same time as the emergence of new ROSAT results, observations of rotational broadening ($v \sin i$– see Stauffer 1991) or photometrically determined rotation periods (e.g. Prosser et al. 1995 and refs. therein) have allowed the evolution of stellar rotation with age to be studied in detail. The prevailing interpretation of these data is that young PMS stars contract and spin-up as they approach the ZAMS after magnetically uncoupling from any circumstellar disk. A variety of disk coupling lifetimes leads to more than an order of magnitude spread in rotation rates at the ZAMS (Bouvier et al. 1997). Meanwhile, AM is lost via a magnetized stellar wind and in order to maintain a big spread in rotation rates, saturation of the AML rate is needed in the fastest rotators. Once on the ZAMS, with a constant moment of inertia, stars lose AM at a mass-dependent rate. Spindown timescales vary from a few tens of Myr for G stars to a few hundred Myr and longer for K and M stars. To reproduce this in models requires that the rotation rate above which AML saturation takes place is such that saturation occurs at roughly constant $N_R$ (Krishnamurthi et al. 1997).

Coronal activity depends on rotation through the dynamo process, hence a correlation between X-ray activity (usually expressed as a fraction of bolometric luminosity - $L_X/L_{bol}$) and rotation is expected. This was well demonstrated
by Stauffer et al. (1994) in the Pleiades, Randich et al. (1996a) in the α Per cluster and Stauffer et al. (1997) in IC 2391/2602. If one looks at G stars in the Pleiades for instance, stars with $v \sin i < 15 \text{ km s}^{-1}$ show an order of magnitude spread in $L_X/L_{\text{bol}}$, with the fastest rotators having the highest activity. This is even more clearly seen when using the more precise $v \sin i$ measurements of Queloz et al. (1998). However, the surprising result was that above a $v \sin i$ of $\sim 15 \text{ km s}^{-1}$, $L_X/L_{\text{bol}}$ seems to reach a saturated plateau value of $10^{-3}$. The reason for this saturation is still unknown. It may be caused by filling of the available coronal volume with plasma or it may be due to a negative feedback in the dynamo mechanism itself. Saturation explains why there is a limited range in $L_X$ among Pleiads of a given mass, even though rotation rates vary by more than a factor 10.

There is a considerable scatter around the rotation-activity correlation when stars with higher or lower masses are added. Following earlier work on magnetic activity by Dobson & Radick (1989), it has been found that including a parameter describing the convective cell turnover time, significantly improves correlations and unifies the view of dynamo generated coronal activity. The new parameter of choice is $N_R$. Fig.1 (from Patten & Simon 1996) shows data from IC 2391, α Per, the Pleiades, Hyades and main sequence field stars. There is still some scatter around this relation, which may be due to time variability/activity cycles, but there appears to be a flattening of activity at $\log N_R = -0.8 \pm 0.2$, irrespective of spectral type, which compares favourably with similar analyses by Stauffer et al. (1997) and Queloz et al. (1998). Because convection zones get deeper and convective turnover times longer in lower mass stars, a uniform saturation $N_R$ indicates a rotation period for saturation that gets longer at lower masses. It is tempting to speculate (see Krishnamurthi et al. 1998) that the coronal saturation coincides with the mass dependent saturation of AML that seems to be required in rotational evolution models (Barnes & Sofia 1996, Krishnamurthi et al. 1997). As yet, the details of (for instance) internal differential rotation are too uncertain for this speculation to be confirmed.

The age dependence of X-ray emission is thought to arise solely as a consequence of the rotation dependence. A clear demonstration of the effect is given by Caillault (1996 - Fig. 1). The XLFs of young clusters have a spread approximately consistent (see below) with the rotation-activity relation (and saturation) and have peak and median values of $L_X$ that decrease with age at a mass-dependent rate. A telling confirmation of the ARAP is that the spectral type of stars at which the saturation value of $L_X/L_{\text{bol}}$ is achieved gets cooler in older clusters as the the higher mass stars spindown below their saturation threshold. Unfortunately, the convergence of rotation rates in solar-type stars by the time they reach the Hyades age, means that at the moment we cannot say much about the history of our own Sun’s activity prior to this epoch. However, the dispersion in rotation and hence coronal emission remains for somewhat longer in lower mass stars (Stern et al. 1995; see also Hawley in these proceedings), because of their longer spindown timescales.

2.2. Time variability

Prior to ROSAT measurements little was known about coronal variability on timescales of months or years and whether it might be responsible for the spreads
Figure 2. The $L_X$ distribution for solar-type stars in the (a) Hyades and (b) Praesepe. The two horizontal lines indicate the approximate sensitivity limits of the ROSAT surveys for the Hyades (lower line) and Praesepe (upper line). The average level of X-ray emission in Praesepe is significantly lower than the Hyades (adapted from Barrado et al. 1998).
Coronal variability is reviewed in these proceedings by Stern, so only a brief summary is given here. Solar coronal variability is a factor of 10 in soft X-rays during its activity cycle (Peres et al.– these proceedings), but how do younger stars behave? The Hyades and Pleiades now have multiple epoch X-ray observations. Both Gagné et al. (1995) and Micela et al. (1996) show that variability in Pleiades stars is smaller than solar variations on timescales of 6 months to ten years. Perhaps 20% to 40% are variable by as much as a factor 2. This might be thought due to the ceiling on X-ray emission provided by saturation, but Stern et al. (1995) show that similar results hold for G and K stars in the Hyades, which are not rotating fast enough for saturation. Stern et al. suggest that the difference in the behaviour of the Sun and younger stars might result from the action of a “turbulent” dynamo in their convection zones, which does not exhibit the cyclical behaviour seen in the Sun. In any case it could be considered fortunate that time variability is not sufficient to cause the spreads in activity seen in young clusters and cannot disguise the ARAP. Unfortunately the $L_X$ of single solar-type stars in older clusters is too low for ROSAT – so we still do not know at what age solar-type variability sets in, although there are numerous examples of short-period binary systems which have been detected at the expected levels of emission (e.g. Belloni 1997 and refs. therein).

3. Unsolved Mysteries

Despite the success of the ARAP in describing most X-ray observations of open clusters, there remain a number of problems that either require a rethink or extension of the paradigm. Among these are the possibility of a “third parameter problem”, the phenomenon of “supersaturation” and whether one cluster at a given age has X-ray properties representative of all similar clusters.

That rotation and spectral-type (or mass) alone might be insufficient to determine X-ray activity was postulated by Micela et al. (1996). They claim that the spread in X-ray activity among slowly rotating G/K Pleiades stars is too large to be accounted for by uncertainties in flux, inclination angle or variability. Similarly, Fig.10 in Stern et al. (1995) shows more than an order of magnitude spread in $L_X$ for F8-G5 Hyades stars, even though their rotation rates are thought to be almost uniform and their variability is demonstrated to be small in the same paper. Micela et al. suggest that the internal rotation profile may be the ingredient that is missing from the ARAP. I believe that this problem may yet be due to a combination of errors in $v \sin i$ measurements (in the case of K stars) and grouping stars with a range of convective turnover times (for late F and G stars). Using more accurate $v \sin i$ measurements, Queloz et al. (1998) show that $L_X/L_{bol}$ is well correlated with $N_R/\sin i$, with only about a factor of 3 spread, which is perfectly consistent with uncertain inclination angles, X-ray flux variability and errors. The key to resolving this issue definitively is to obtain accurate rotation periods for many more stars, rather than new X-ray observations.

“Supersaturation” is the observed phenomenon that at very fast rotation rates, $L_X/L_{bol}$ appears to decrease by a factor of 3-5 below the canonical saturation limit of $10^{-3}$ (Prosser et al. 1996; Randich 1998). Because it affects
only the fastest rotating late-type stars \( (v \sin i > 100 \text{ km s}^{-1}) \) and there are only a few \( (\sim 10) \) of these in the very young \( \alpha \) Per and IC 2391/2602 clusters, it is still not clear whether supersaturation sets in at a particular rotation rate or a particular \( N_R \). The latter is not favoured by observations of dMe stars (see James et al. in these proceedings). An explanation for supersaturation is not obvious. Randich (1998) suggests that it may represent a fall-off of the dynamo mechanism itself or perhaps a shift in the distribution of the radiative losses out of the \( \textit{ROSAT} \) band to either hotter or cooler temperatures. The latter explanation may draw some support from the few X-ray spectra available for stars in the Pleiades (Gagné et al. 1995) which indicate that the fastest rotating G stars have hotter coronae than the slow rotators. Unfortunately there are almost no nearby field stars that rotate fast enough to exhibit supersaturation and have accurate X-ray spectra that could test this hypothesis. Perhaps a more likely explanation is centrifugal shrinkage of the available coronal volume at very high rotation rates.

Most of the early interpretation of X-ray observations relied on the assumption that one cluster was representative of all clusters at the same age. In the \( \textit{ROSAT} \) era, this assumption can be tested (see Table 1). One of the most important results of this decade, illustrated in Fig.3, was that the coronal activity of low mass stars (especially solar-type) in Praesepe was significantly lower on average than those in the Hyades at the same age, although peak \( L_X \) values were similar (Randich & Schmitt 1995). Explanations range from contamination by non-members in the Praesepe sample, differing binary fractions or orbital distributions, differing initial conditions (specifically the AM distribution) or rotational evolution (perhaps influenced by composition differences – Jeffries et al. 1997). Mermilliod (1997) shows that the rotation rate distributions in the two clusters are similar and Barrado y Navascué¡ et al. (1998) find that contamination with non-members is unlikely. Although much more work needs to be done on identifying and parameterizing binaries in Praesepe, a genuine explanation remains elusive. Observationally, the situation has now become more confusing. Randich et al. (1996b) find that the pattern of X-ray emission in the F/G stars of the similarly aged Coma Berenices cluster resembles the Hyades rather than Praesepe, whereas the X-ray activity of F/G stars in NGC 6633 and F stars in IC 4756 is less than the Hyades (Totten et al. these proceedings, Randich et al. 1998). Deeper observations of Praesepe, NGC 6633 and IC 4756 to remove the upper limits will certainly assist interpretation, as will careful optical work to identify spectroscopic binaries. AXAF offers the opportunity to extend these tests to more distant open clusters with a range of ages, composition and richness.

### 4. High Spatial Resolution

High spatial resolution is useful in several distinct ways in studies of open clusters. First, as one moves towards more distant open clusters, the angular separation between cluster X-ray sources becomes small and accurate analysis becomes difficult as PSFs start to overlap. A good example is NGC 2516 (Jeffries et al. 1997), where 159 X-ray sources were found within 20' of the centre of a PSPC pointing, and multiple PSF fitting (analogous to DAOPHOT for optical
photometry) was required. This cluster has been re-observed at about 8 times the spatial resolution (but less sensitivity) with the HRI (FWHM~3") and the results are shown in Fig.3. Essentially all the sources found by the HRI are also extracted from the PSPC data at the right positions. At this sensitivity NGC 2516 represents the most distant cluster (for its age) which could be studied with the spatial resolution of the PSPC. As nowhere near all the cluster members were detected by the PSPC one would like to go deeper, but it is clear that HRI-like spatial resolution will be required to do this. The problem will be more acute for more distant clusters with a similar “richness”.

A different problem is the identification of X-ray sources with their optical counterparts. In clusters close to the Galactic plane (and more distant clusters will tend to be so), there may be several candidate stars within each X-ray error circle. Clearly, improvements in spatial resolution concomitantly reduce the number of possible optical counterparts. For most nearby clusters the increase in resolution from PSPC to HRI is not too important from this perspective (e.g. Simon & Patten 1998), but for others near the Galactic plane or for deeper studies with fainter possible optical counterparts, higher spatial resolution than offered by the PSPC is absolutely essential (e.g. Giampapa et al. 1998).
Figure 4. A colour-magnitude diagram for NGC 2547 together with those stars residing inside HRI X-ray error circles (squares).

A related problem that plagues studies (not just in X-rays) of low mass stars in open clusters is a lack of firm membership lists for faint stars. Proper motions and photometric selection can be useful among nearby clusters, but as one moves to more distant clusters, which tend to be projected against the Galactic plane, both background contamination and small proper motions become problematic. An alternative approach, which relies on the ARAP, is to find low mass members by X-ray selection, because the contrast in X-ray flux between young, low mass cluster stars and a general field population is large. This approach has now been used in a number of young clusters where optically selected membership catalogues are either absent or very uncertain (e.g. Prosser et al. 1994; Patten & Simon 1996). A combination of photometric selection plus small X-ray error circles can be especially powerful and if the X-ray survey is deep enough then one can be reasonably sure that the selected members are a complete sample, rather than biased towards high activity levels. A recent example is shown in Fig. 4. NGC 2547 is a young cluster observed with the HRI (Jeffries & Tolley 1998). The ∼6 arcsec error circles contain one star on average and the majority of these form a sequence along the expected locus of the cluster in a colour-magnitude diagram. Less than one correlation is expected by chance in this part of the CMD, so these stars must be genuine cluster members. Furthermore, the X-ray survey is sufficiently deep that the X-ray selected G and K stars are expected to be a complete sample from which other investigations can be based.
5. AXAF and XMM

High resolution spatial imaging, moderate spectral resolution and increased effective area over ROSAT are the key attributes of the AXAF satellite. The ACIS instrument is capable of 1 arcsec resolution with spectral resolution of \( \sim 20 \) at \( \sim 2 \) keV over a 16 arcmin field. The ACIS sensitivity threshold will be a factor of 3-5 better than the PSPC/HRI for the same exposure time. The HRC instrument has even better spatial resolution over a larger 31 arcmin field but little spectral resolution. XMM has a larger overall effective area and the capability of providing spectral resolution of several hundred for individual targets. Together, the capabilities of the two instruments will make significant advances in our understanding of the X-ray evolution of cool stars in open clusters.

- For nearby clusters (the Pleiades and NGC 2516 in AO-1), X-ray emission can be probed further down the main sequence to see if the nature of the dynamo changes in fully convective stars or even brown dwarfs.

- The spectral resolution will allow detailed modelling of the X-ray spectra. At present, a single, crude spectral model is normally assumed to convert from count rate to flux. We will be able to see if coronal temperatures continue to increase in the most rapidly rotating stars and whether a shift of flux to higher energies causes supersaturation in the ROSAT pass band. XMM will be able to provide detailed, high resolution spectroscopic studies of even low activity stars in both the Hyades and Pleiades at \( L_X \) thresholds of roughly \( 10^{28} \) and \( 10^{29} \) erg s\(^{-1}\) respectively, in reasonable exposure times.

- For the first time, the detection of X-ray emission from main sequence stars in clusters older than the Hyades will be possible. The AXAF mission time should be long enough to also get second epoch observations to study variability in these older clusters.

- AXAF should be able to study clusters out to distances of 1 kpc and the high spatial resolution means that even clusters with low \( b \) will be accessible. Deeper observations of clusters at the same age as the Hyades are required to remove the remaining ambiguities posed by ROSAT upper limits. Several clusters at the same age as the Pleiades (\( \sim 100 \) Myr) and NGC 6475 (\( \sim 300 \) Myr) can be studied.

- More distant, compact open clusters can be examined to find more of the rare open clusters with ages between 10 and 40 Myr, which are so important in understanding the history of AML and circumstellar disks.

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