

# X-RAY CORONAE FROM STARS

R. PALLAVICINI

*Osservatorio Astronomico di Palermo*

*Palazzo dei Normanni, 90134 Palermo, Italy*

## 1. Introduction

A number of major advances in stellar coronal physics have occurred since 1990 mainly as a consequence of imaging observations by ROSAT and spectroscopic observations by ASCA. These can be summarised as follows:

1. an all-sky survey has been performed by ROSAT at a sensitivity of  $\sim 2 \times 10^{-13}$  erg cm<sup>-2</sup> s<sup>-1</sup>, complemented by pointed observations an order of magnitude deeper;
2. complete mapping and deeper pointings have been obtained for virtually all open clusters closer than  $\sim 500$  pc, and covering the age range from  $\sim 30$  Myr to  $\sim 700$  Myr;
3. complete mapping and deeper pointings have been obtained for several Star Forming Regions (SFRs) covering the age range  $\sim 1$  to  $\sim 10$  Myr;
4. spectroscopic observations of bright coronal sources have been obtained with EUVE and ASCA allowing the derivation of the temperature structure and elemental abundances.

In this paper I will discuss briefly the second and fourth topic in the above list, i.e. imaging observations of open clusters by ROSAT and spectroscopy of bright coronal sources by ASCA. X-ray observations of young stellar objects in SFRs are discussed by Montmerle elsewhere in this volume.

## 2. Imaging observations of open clusters

Open clusters form homogeneous samples of stars with approximately the same age and chemical composition, but different masses. Prior to ROSAT, only two clusters (the Hyades and the Pleiades) had been observed in sufficient detail at X-ray wavelengths. ROSAT has observed a dozen nearby open clusters covering the age range from  $\sim 30$  Myr to  $\sim 700$  Myr. These

observations allow investigating the evolution of stellar angular momentum with age in stars of different masses and convection zone depths.

A comparison of the X-ray luminosity functions of different clusters shows that X-ray emission steadily decreases from younger clusters (like IC2602 and IC2391 at  $\sim 30$  Myr or  $\alpha$  Per at  $\sim 50$  Myr) to intermediate age clusters (like the Pleiades and NGC2516 at  $\sim 70$ -100 Myr), to older clusters (like the Hyades, Coma and Praesepe at an age of  $\sim 500$ -700 Myr). While this is generally true for solar-type stars (cf. Randich 1997 and references therein), there are significant differences with regard to the age dependence of X-ray luminosity functions for stars of different spectral types. For instance, while G and K stars in  $\alpha$  Per ( $\sim 50$  Myr) are brighter in X-rays than stars of the same spectral type in the Pleiades (age  $\sim 70$  Myr), this is not true anymore for M dwarfs, which show virtually the same X-ray luminosity function in  $\alpha$  Per and in the Pleiades (Randich et al. 1996). This can be understood as a consequence of magnetic braking by stellar winds, the braking time scale being determined by the depth of the convection zone. For G and K stars, the convective zone is sufficiently shallow to allow a significant braking in the time interval from the age of  $\alpha$  Per to that of the Pleiades, while there is no significant angular momentum loss in the same time interval for M stars with deeper convective zones.

Although the general picture is quite consistent, there are a number of disturbing facts, indicating that the current scenario is at best only a first order approximation. For instance, late-type stars in the Praesepe cluster (which has the same age and chemical composition as the Hyades) are much weaker in X-rays than similar stars in the Hyades (Randich & Schmitt 1995). On the contrary, F and G stars in the Coma cluster (at an age of  $\sim 500$  Myr) are in good agreement with the Hyades. Jeffries et al. (1997) have found similar discrepancies between NGC2516 (a southern "twin" of the Pleiades) and the general pattern shown by the Pleiades, NGC6475 ( $\sim 200$  Myr) and the Hyades. They have attributed it to the subsolar metallicity ( $[\text{Fe}/\text{H}] = -0.3$ ) of NGC 2516, suggesting that metallicity may be an additional parameter (through its effects of the depth of the convection zone) affecting angular momentum evolution.

### 3. Spectroscopy of coronal sources

Stellar coronae have thermal spectra rich in emission lines.  $1 - T$  and  $2 - T$  models and solar abundances were usually assumed in the analysis of early observations with low spectral resolution, such as those obtained with the IPC detector on *Einstein* and the PSPC detector on ROSAT. Only recently, with the EUVE and ASCA missions, it has become possible to exploit the diagnostic potential of X-ray coronal spectra, to derive the temperature

distribution and elemental abundances.

Somewhat surprisingly, most (albeit not all) coronal sources observed with ASCA (and EUVE as well) showed reduced metal abundances (by typical factors of 3 to 5) with respect to *solar* abundances (White 1996, and references therein). In many cases, the best fit to the ASCA CCD spectra over the range 0.5 to 10 keV is obtained with a  $2 - T$  thermal model with variable non-solar abundances, i.e. by leaving individual elements free to vary. In other cases, a sufficiently good fit is obtained by leaving only the overall metallicity free to vary, i.e. by varying the individual abundances in the same proportion with respect to solar abundances. When the individual abundances are left free to vary, they show little evidence for a FIP effect, although evidence for a FIP effect has been reported for some of the stars observed with EUVE. At any rate, if a FIP effect is present, it is the opposite to that observed in the solar corona, where ions with low First Ionization Potential (FIP) like Iron are enhanced with respect to ions with high FIP.

The fact that the coronal abundances measured by ASCA and EUVE in a given star are typically lower than solar photospheric abundances does not imply necessarily that they are also lower than the photospheric abundance of the same star. Most stellar coronal sources for which medium resolution spectroscopy has been obtained with ASCA are bright RS CVn and Algol-type binaries, which are known to have often subsolar photospheric abundances (e.g. Randich et al. 1994) although it is yet unclear whether the observed weakness of the optical absorption lines is due to lower metallicity or rather to the effect of surface activity. For instance, the RS CVn binary  $\lambda$  And observed by ASCA (Ortolani et al. 1997) was found to have a coronal abundance a factor 5 lower than solar but perfectly consistent with its measured photospheric abundance.

While the subsolar coronal abundances found by ASCA in several RS CVn and Algol-type binaries may not be inconsistent with the photospheric abundances of these stars as a class, there are at least a few cases in which there is a clear discrepancy between the measured coronal and photospheric abundances. One case is the young rapidly rotating star AB Dor observed simultaneously by ASCA and EUVE (Mewe et al. 1996). The coronal metallicity of this star is  $\sim 0.3$  solar in spite of the fact that AB Dor is a ZAMS star with a measured photospheric abundance that is solar. Another case is the young active star HD35850 (Tagliaferri et al. 1997): again the coronal metallicity measured by ASCA is  $\sim 0.3$  while the measured photospheric metallicity is solar. On the contrary, the active giant  $\beta$  Cet observed by both ASCA and SAX shows a solar photospheric abundance (Maggio et al. 1997), while the analysis of a recent SAX observation of Capella gives a coronal metallicity  $\sim 0.8$  solar (Favata et al. 1997) consistent with both the EUVE value and the photospheric abundance, but at variance with

previously reported results from ASCA (e.g. White et al. 1996).

#### 4. Conclusions

The observations carried out over the past few years have allowed substantial progress to be made in our understanding of stellar coronal emission. As an example, I have illustrated here only two problems, that of late-type stars in open clusters and of elemental abundances in bright coronal sources. There are several other areas in which the new observations have provided crucial information. For instance, ROSAT data have given further support to the shock heating model for early-type stars; on the other hand, cool dwarfs offer the best opportunity to probe convection, angular momentum evolution and dynamos. The existence of a coronal/wind dividing line (DL) among cool giants has been confirmed by ROSAT, but the origin of this DL remains speculative. Moreover, the DL seems to disappear among supergiants and all hybrid stars are in fact detected in X-rays. PMS stars in the age range  $\sim 1$  to 10 Myr have been confirmed to be strong X-ray sources, extending to younger ages the dependence of coronal emission on age already shown by cluster data. More importantly, ROSAT and ASCA have detected X-rays from very young ( $\sim 0.1$  Myr) embedded objects in several SFRs (Koyama et al. 1996) showing that X-rays are a new powerful tool to study star formation and early stellar evolution. Finally, the puzzling results obtained by ASCA and EUVE on coronal abundances of active stars point at the existence of photospheric/coronal abundances anomalies or at problems with the atomic physics entering the spectral codes used in the analysis.

#### References

- Favata, F., Mewe, R., Brickhouse, N.S., Pallavicini, R., Micela, G., 1997, *A&A* 324, L37  
 Jeffries, R.D., Thrurston, M.R., Pye, J.P., 1997, *MNRAS*, in press  
 Koyama, K., Hamaguchi, K., Ueno, S., Kobayashi, N., Feigelson, E.D., 1996, *PASJ* 48, L87  
 Maggio, A., Favata, F., Peres, G., Sciortino, S., Rosner, R., 1997, *A&A*, in press  
 Mewe, R., Kaastra, J.S., White, S.M., Pallavicini, R., 1996, *A&A* 315, 170  
 Ortolani, A., Maggio, A., Pallavicini, R., Sciortino, S., Drake, J.J., Drake, S.A., 1987, *A&A* 325, 664  
 Randich, S., 1997, in G. Micela, R. Pallavicini and S. Sciortino (eds.), *Cool Stars in Clusters and Associations: Magnetic Activity and Age Indicators*, in press  
 Randich, S., Giampapa, M.S., Pallavicini, R., 1994, *A&A* 283, 893  
 Randich, S., Schmitt, J.H.M.M., 1995, *A&A* 298, 115  
 Randich, S., Schmitt, J.H.M.M., Prosser, C.F., Stauffer, J.R., 1996, *A&A* 305, 785  
 Tagliaferri, G., Covino, S., Fleming, T.A., Gagné, M., Pallavicini, R., Haardt, F., Uchida, Y., 1997, *A&A* 321, 850  
 White, N.E., 1996, in R. Pallavicini and A.K. Dupree (eds.), *Ninth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, ASP Conference Series 109, 193