38

ROBERTO PALLAVICINI*

High-energy radiation from outer stellar atmospheres

Although the Sun had been known to be a source of X-ray and ultraviolet radiation since the late 1940s, it was only in the late 1970s that normal stars of nearly all spectral types and luminosity classes were recognized to be sources of high-energy radiation detectable from space (see Mewe 1996 for a historical perspective). The origin of this high-energy emission from normal (i.e. non-accreting) stars constitutes a fundamental and yet unsolved problem in stellar astrophysics, which space observations have helped to elucidate over the past 20 years. It was quite obvious from the very first observations that the generation of high-energy photons by thermal processes, such as the ones usually observed in normal stars, requires temperatures far in excess to those responsible for the stellar optical radiation. In particular, it requires that the temperature profile in stellar atmospheres, after reaching a minimum in the upper photosphere, rises again, attaining values of one to several million degrees in the corona. These outer atmospheric layers, where the temperature increases outwards through the chromosphere, transition region and corona, had been known and widely studied for a long time in the case of the Sun, but it was only much later with the advent of grazing incidence X-ray telescopes and sensitive X-ray detectors that their existence for the vast majority of stars was definitely proved.

The study of high-energy radiation from normal stars is a powerful diagnostic tool for the physical conditions in outer stellar atmospheres and for the processes in the stellar interiors that are at the origin of coronal heating. X-ray and UV radiation in fact provides information on non-radiative heating mechanisms as well as on the processes that lead to wind acceleration and mass loss. In the case of cool stars – which possess subphotospheric convective zones – both the high coronal temperatures and the various manifestations of stellar activity appear to be related to the generation of magnetic fields through a dynamo process that involves rotation and convection. Thus, observations of stellar chromospheres, transition regions and coronae, albeit limited to the outer atmospheric layers, allows us to put constraints also on the physical processes that occur deep in the interior of stars, with important implications for our understanding of stellar structure and evolution. Moreover, observations of stars in different evolutionary stages, from the early phases of contraction to the main sequence to the late stages of evolution out of it, allow for the investigation of the effects of magnetic braking and angular momentum loss on the generation of magnetic fields and on the heating processes.

The traditional view, first developed in the case of the Sun, attributed the temperature inversion that occurs in the outer stellar atmospheres to shock dissipation of acoustic waves generated in the subphotospheric convective zone. Although this theory is probably still valid for the Sun's lower chromospheric layers and for non-magnetic regions, it fails badly for solar magnetic regions, for active stars and in general for stars, both hotter and cooler than the Sun, with an internal structure significantly different from the solar one. For cool stars, magneto-acoustic and Alfvén waves and/or resistive dissipation of electric currents are more likely to be responsible for the observed high-energy radiation, thus stressing the importance of magnetic fields in the outer atmospheres of these stars. Hot stars, which do not have outer convective zones, are also observed to be sources of X-rays, but high-energy emission in this case is more likely due to shock dissipation in their massive radiatively driven winds rather than to the presence of a high-temperature corona.

* Osservatorio Astronomico di Palermo, Italy

Roberto Pallavicini, The Century of Space Science, 875–894

In this chapter, I will review X-ray and UV emission from outer stellar atmospheres with emphasis on X-ray emission from the coronae of late-type stars, that is stars that possess subphotospheric convective zones. According to the usual classification based on their optical spectra, these stars cover the spectral types from F to M, and all luminosity classes from dwarfs to supergiants. Along the main sequence, the effective temperature decreases from about 7000 K to less than 3000 K, the mass decreases from about 1.7 solar masses to one-tenth of a solar mass and the radius decreases from about 1.3 to a few tenths of the solar radius. On the contrary, the convection zone depth increases from a negligible fraction of the stellar radius in early F-type stars to the whole stellar radius in late M dwarfs. The wide range of physical parameters covered by F to M stars along the main sequence, not to mention the wider range provided by the inclusion of giants, offers a variety of different conditions for the generation of magnetic fields and for the heating of the outer atmospheric layers. In addition, the broad range of ages and evolutionary stages covered by cool stars implies also different values of rotation rates and hence of the efficiency of magnetic field generation by the dynamo process. All this offers to our physical speculations a much more complex picture that the one made possible only by observations of the Sun. The X-ray and UV observations carried out from space during the past 20 years have largely unravelled this complex picture taking us to the point where we can finally start to understand the physical processes at the origin of coronal activity in different types of stars.

EARLY RESULTS ON STELLAR X-RAY EMISSION

The beginning of stellar X-ray astronomy

Before the launch of the International Ultraviolet Explorer (IUE) and of the Einstein Observatory (formerly HEAO 2) in 1978, there was only a handful of stellar coronal sources, besides the Sun, known to emit X-ray and UV radiation (Mewe 1979). They were either very close objects (e.g. α Centauri) or very active stars with coronal emission many orders of magnitude higher than that of the Sun. Most of the latter objects were close binary systems of the RS Canum Venaticorum (RS CVn) type, a class of binary stars known for their extreme activity at optical and radio wavelengths. One of these objects, Capella, was indeed the first non-solar coronal X-ray source to be detected in 1974 during a rocket flight and is still the brightest X-ray source among normal stars, except for the Sun. This early discovery was soon followed by the detection with the first High Energy Astronomical Observatory (HEAO 1) of a number of other RS CVn stars with typical X-ray luminosities in the range of 10^{30}–10^{31} erg s^{-1} in the soft X-ray band. This is 1,000 to 10,000 times more than the average X-ray luminosity of the Sun or of quiet solar-type stars like α Cen. At any rate, X-ray emission at appreciable levels was thought at that time to be limited to somewhat peculiar objects and not to be a general characteristic of all types of stars.

Neither was there much expectation from a theoretical point of view of detecting stellar coronal emission (Mewe 1979). The mechanism of coronal heating generally accepted at that time was shock dissipation of acoustic waves generated in subphotospheric convective zones. In spite of large uncertainties present in available estimates of the power dissipated by acoustic waves, the theory invariably predicted that maximum dissipation should occur around spectral types F and G, decreasing rapidly towards later spectral types along the main sequence. It was not expected therefore that X-ray emission could be detected in K and M dwarfs, nor in early-type stars that do not possess outer convective zones. Even more importantly, the acoustic heating theory predicted that stars at a given position in the HR diagram should all have the same level of chromospheric and coronal emission, which in turn should depend only on the properties of their convective zone and on the efficiency of generation of acoustic noise. Spatially resolved observations of the solar chromosphere and corona (which showed the presence of localized regions of enhanced emission associated with regions of stronger magnetic fields) were clearly at variance with this simplified picture; however, the effect of magnetic fields was considered only as a second-order perturbation which could hardly change the overall picture. As for early-type stars, acoustic waves could not be driven by convection but it was suggested that waves could be amplified by radiation pressure leading some authors to believe that early-type stars might eventually be detected in X-rays.

The early observations by IUE and Einstein showed that these expectations were fundamentally wrong. In particular, the Einstein Observatory showed that virtually all stars, with the exception of A-type dwarfs and of late K and M giants, were X-ray emitters (Vaiana *et al.* 1981). For late-type stars, there was little or no dependence of the X-ray emission on spectral type, in contrast with the predictions of the acoustic theory. Only for early-type stars was there a clear dependence of the X-ray emission on the stellar bolometric luminosity. For late-type dwarfs of spectral types F to M a broad range (more than three orders of magnitude) of coronal emission levels existed at each effective temperature, indicating that parameters other than the position of a star in the HR diagram (i.e. effective temperature and luminosity) were responsible for the activity level of stellar outer atmospheres. These early observations clearly demonstrated that the acoustic theory was basically untenable as far as coronal heating is concerned and that other mechanisms, possibly involving magnetic fields, were to be

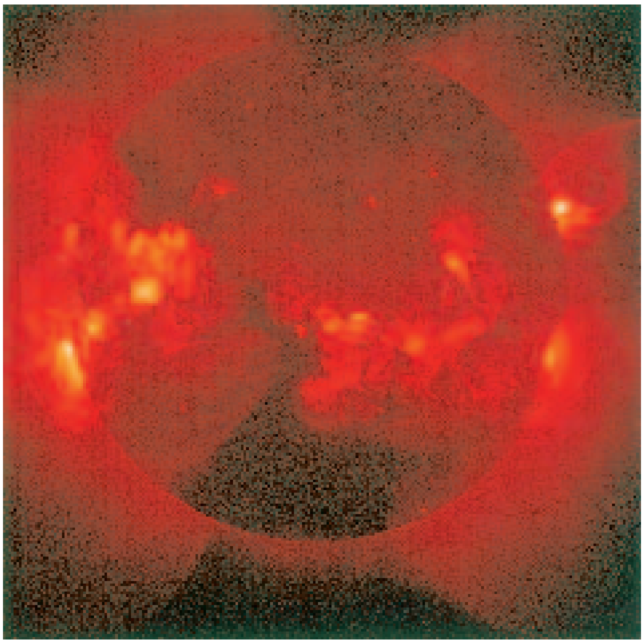

Figure 1 Soft X-ray image of the solar corona obtained on 27 January 1992 with the Soft X-ray Telescope (SXT) on the Japanese satellite Yohkoh. (Courtesy of the Institute of Space and Astronomical Sciences.)

explored. These results for stars were in line with increasing evidence from solar observations that X-ray-emitting coronae are dominated by magnetic field effects (Rosner *et al*. 1985), and that surface magnetic fields are perhaps the dominant factor in determining the structure and variability of late-type coronae and in providing for their heating (Figure 1).

It is interesting to note that this interplay of solar and stellar results, all pointing in the same direction, is itself a consequence of space observations at X-ray and UV wavelengths, being carried out at about the same time, but with different emphasis and different objectives, for the Sun and stars. In the case of the Sun, sensitivity is not a problem, since the Sun, in spite of being an intrinsically weak X-ray and UV source, appears to us very strong because of its proximity. The Sun is the only star which appears to us as an extended source; it is therefore not surprising that the emphasis of solar research was, and still is, in obtaining high-spatial-resolution observations which allow for the study of fine details in the solar atmosphere. The X-ray and UV observations obtained in 1973–74 by *Skylab* and in 1980 by SMM, as well as the solar images obtained more recently by Yohkoh, SOHO and TRACE, revealed a highly structured outer atmosphere, where the coronal plasma appears confined by the magnetic field in loop-like structures tracing the field lines. The same observations also revealed that the solar corona is highly dynamic in response to fluctuations in the heating rate. All this suggested that magnetic fields not only confine the coronal plasma (since the magnetic pressure exceeds the gas pressure in the corona), but are also responsible for the heating of the plasma to temperatures far in excess of a star's effective temperature.

Coronal X-ray emission in late-type stars

The broad range of X-ray emission levels observed for late-type stars of similar effective temperatures was soon found to be related to stellar rotation and age, thus enforcing the notion that dynamo-generated magnetic fields are responsible for coronal heating in stars of late spectral types (Pallavicini *et al*. 1981). Although a fully consistent dynamo theory does not yet exist, not to mention a generally accepted coronal heating theory, a qualitative expectation is that the efficiency of dynamo action should increase with stellar rotation rate in stars that possess subphotospheric convective zones. We may expect, therefore, that the activity level of a star, as it results from the cumulative effects of the multitude of magnetically confined coronal structures that form its outer atmosphere, should depend on the rotation rate, or better on a combination of rotation and convection zone properties. This combination of dynamo factors is often parameterized by means of a Rossby number (Noyes *et al*. 1984) defined as the ratio of the star rotation period P_{rot} to a colour-dependent convective turnover time τ_{conv}, computed at the base of the convective zone (where most of the dynamo action is believed to occur). The observed dependence of stellar chromospheric and coronal emission on either rotation rate or Rossby number is a strong, albeit only qualitative, support of this interpretation. The details should depend on the still poorly understood properties of the dynamo process and of the conversion of magnetic fields into plasma heating.

Since coronal emission among late-type stars appears to depend on both rotation and age, a relevant question is whether these parameters are related to each other and, if so, which of the two is the primary one for coronal heating. The existence of a dependence on age was demonstrated by observations of open clusters, that is by homogeneous samples of stars with approximately the same age and chemical composition. It was evident from early IUE and Einstein observations of the Hyades and the Pleiades, and from the comparison of solar-type stars in these clusters with the much older Sun, that there was a dependence of chromospheric, transition region and coronal emission upon age (Stern *et al*. 1981, Caillault and Helfand 1985, Micela *et al*. 1990). On the other hand, it is well known that late-type stars with outer convective zones suffer angular momentum loss during their main sequence lifetime, owing to the braking action of magnetized stellar winds. As stars get older, they rotate more slowly, and their chromospheric and coronal emissions (which have been found by Einstein and IUE to be related one to the other, e.g. Ayres *et al*. 1981) both decline with age. Rotation, rather than age, appears therefore to be the primary factor, at least for stars that have already reached the main sequence (the situation may be more complex for pre-main sequence stars, owing to the interaction of the young star with the surrounding disk). That rotation is indeed the primary factor is confirmed by the high activity and strong coronal emission of RS CVn binaries which are relatively old stars (a few Gyr) that still rotate rapidly because of the tidal interaction of the two components in a close binary system.

The above picture was developed in the early 1980s at the Center for Astrophysics in Cambridge, MA, by the group responsible for the early analysis of the stellar data from the Einstein Observatory. This group, led by Giuseppe S. Vaiana (an Italian scientist who, not surprisingly, had worked previously on X-ray observations of the solar corona, and who had been responsible for one of the main instruments on ATM-Skylab), greatly benefited from the interaction with a number of Guest Investigators from all parts of the world (Jeff Linsky, Tom Ayres, Fred Walter, Rick Harnden, Joe Cassinelli, Rolf Mewe, Bob Stern and Thierry Montmerle, just to mention a few) and included at that time a number of young scientists (Bob Rosner, Leon Golub, Roberto Pallavicini, Jürgen Schmitt) who continued for many years to work in the field of stellar X-ray astronomy. Later, it also included a number of young researchers from the Astronomical Observatory of Palermo, where Vaiana, upon his return to Italy, established an active centre of stellar corona research. The interpretation of stellar X-ray activity in terms of dynamo-generated magnetic fields and solar analogues was largely suggested by previous work on chromospheric Ca II H and K emission and on its dependence on rotation and age, as well as by the lesson learned from spatially resolved observations of the solar chromosphere, transition region and corona. It received further support from the wealth of ultraviolet data provided at about the same time by IUE on stellar chromospheres and transition regions up to temperatures of about 10^5 K (see Jordan and Linsky 1987 for a review).

Late-type giants

A further surprise in these early days came from the observations of late-type giants and supergiants. Whereas yellow giants are typically X-ray emitters, sometimes at very strong levels, this was not the case for red giants later than spectral type K2 for luminosity III giants and of spectral type G0 for supergiants. On the basis of UV and X-ray observations from IUE and Einstein, the presence of a dividing line (DL) in the HR diagram was inferred (Linsky and Haisch 1979, Maggio *et al*. 1990), separating stars with high-temperature coronae and low mass losses (to the left of the DL) from stars with high mass losses and the absence of high-temperature plasma (to the right of the DL; note that the cool, low-speed winds of late-type giants are fundamentally different from the hot, high-temperature winds of early-type stars). A class of stars was also found (the so called 'hybrid' stars) which have both large mass losses and plasma in excess of 10^5 K in their outer atmospheres, suggesting that the transition between the two classes of evolved stars (with and without coronae) may not be as abrupt as originally thought. For some late giants (for instance Arcturus) extremely low upper limits to their X-ray luminosity (as low as 10^{25} erg s^{-1}, Ayres *et al*. 1991) have now been established, which indicates that the X-ray surface fluxes in these evolved low-gravity stars must be many orders of magnitude lower than in solar coronal holes. The onset of strong mass losses nearly coincident with the disappearance of hot coronae strongly suggests a causal relationship between the two phenomena. By analogy with the Sun, the presence of a high-temperature corona in a late-type star implies the existence of magnetically confined structures which are denser and hotter than the surrounding regions. On the contrary, areas of open field lines in the Sun (i.e. coronal holes) are somewhat cooler and much less dense than the emitting loops: apparently the energy deposited in these regions (by either magneto-acoustic waves or electric currents) goes into accelerating the wind and in enhancing mass losses rather than into plasma heating. By analogy, the transition across the DL could be interpreted as a change of magnetic topology in the outer atmospheres of cool stars, from a corona dominated by closed magnetic structures (similar to solar coronal loops) to an essentially open corona, with most field lines being open to the interplanetary space. Whether this picture is correct, and how the supposed change of magnetic topology relates to the dynamo process and to the internal changes experienced by a star during its evolution out of the main sequence, remain questions to be solved.

X-rays from stellar winds in early-type stars

The situation with early-type (O-B) stars is completely different. Their X-ray luminosity, ranging from 10^{29} to 10^{34} erg s^{-1}, is virtually independent of rotation, while it depends on bolometric luminosity (albeit with some scatter). This suggested that the X-ray emission might be related to the strong, high-speed radiatively driven winds known to exist in these massive stars. Early models of X-ray emission from hot stars assumed the presence of a thin, high-temperature corona at the base of the wind, possibly confined by fossil magnetic fields (Cassinelli and Olson 1979). This model, however, was not confirmed by spectral observations with the Einstein Solid State Spectrometer (SSS) which did not

http://www.springer.com/978-0-7923-7196-0

The Century of Space Science
Bleeker, J.A.; Geiss, J.; Huber, M. (Eds.)
2001, XLIX, 1846 p., Hardcover
ISBN: 978-0-7923-7196-0