ROSAT All-sky survey observations of normal stars
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Introduction and summary

1.1 X-rays from 'normal' stars

1.1.1 Introduction

This thesis focuses on low-energy ('soft') X-ray emission from 'normal' stars, where 'normal' refers to stars, sometime during their evolution after reaching the main sequence, but excluding the very end stages. Moreover, 'normal' stars should show no peculiarities in chemical composition, nor are they members of a binary in which they are tidally coupled to the companion star.

Several mechanisms have been proposed for the X-ray emission of astronomical objects, e.g., thermal radiation (effective for temperatures above a million Kelvin), synchrotron radiation (relativistic electrons in a magnetic field), and inverse Compton scattering (relativistic electrons colliding with photons). Thermal radiation can be generated in free-free emission (bremsstrahlung); if the temperature is not so high that all atoms are fully ionized (i.e., less than a few $10^7$ K), radiation can be produced by bound-bound and by free-bound emission. If the emitting medium is optically thick and nearly isothermal, its radiation approaches the Planckian black-body spectrum. Synchrotron radiation can be recognized by the powerlaw shape of its spectrum, and by its polarization. Inverse Compton scattering also requires relativistic electrons and usually results in a power-law spectrum. X-rays from 'normal' stars are expected (and often observed) to be of thermal origin, because the highly energetic processes that could create relativistic electrons usually do not occur in these stars at the required luminosity levels (except during stellar flares).

The following subsections briefly review our current knowledge of the low-energy X-ray properties of 'normal' stars. These stars have been divided in three groups, according to their spectral types.

1.1.2 Late-type stars

Stars with spectral types later than about G0, of which the Sun is the nearest example, are known to be soft X-ray emitters. The Sun has been observed in X-rays since 1949, when a sounding rocket with a photon counter on board was pointed at the Sun (Friedman et al. 1951). The ATM instruments on board Skylab in the early seventies (Withbroe & Noyes 1977; Vaiana & Rosner 1978), the Solar Maximum Mission in 1980 (Simnett 1982), and the recent YOHKOH mission (Uchida et al. 1992) have produced a large amount of
data on the complex and highly variable X-ray emitting regions on the Sun. The first evidence that other ‘normal’ cool stars emit soft X-rays was obtained with the detection of X-rays from Capella in a rocket flight in 1974 (Catura et al. 1975), and confirmed later by the Dutch X-ray satellite ANS (Mewe et al. 1975).

The discovery of hot stellar coronae had been preceded by the study of warm chromospheres (with $T \geq 10^4$ K) around late-type stars, which are indicated by the emission peaks in the cores of the Ca II H&K resonance lines (Wilson 1963; Skumanich et al. 1975). The solar analogue suggests (1) that most of the chromospheric emission originates in an intricate and variable magnetic structure, and (2) that this magnetic structure could also support a hot corona (Mewe & Zwaan 1980).

The Einstein and EXOSAT missions contributed greatly to a better understanding of late-type stars as X-ray emitters. It appeared that the majority of the stars with spectral types later than about G0 show X-ray emission. No X-ray emission was detected from single, very late-type giants and supergiants, which lead to the so-called coronal dividing line in the HR diagram pointed out by Linsky & Haisch (1979).

Comparison between soft X-ray data, UV (mainly IUE) data and Ca II H&K measurements revealed that the outer-atmospheric emissions from the various temperature regimes are strongly correlated (see Zwaan 1991; Ayres et al. 1981). Comparison with measurements of magnetic-field parameters indicated that the outer-atmospheric emissions do originate in magnetic structure (Schrijver 1991). The outer-atmospheric emissions appear to increase with increasing stellar rotation rate (Hartmann & Noyes 1987).

The soft X-ray emission and the other outer-atmospheric emissions are qualitatively accounted for by a scenario based on outer-atmospheric heating within magnetic structure created by dynamo action within the stellar convective envelope below the atmosphere (see Weiss 1992). However, this picture of magnetic activity leaves many questions of quantitative theory open: we do not really understand the dynamo action in stellar convection zones. Also the mechanisms of the outer-atmospheric heating in the various temperature regimes are far from completely understood. And while it seems plausible that the magnetically controlled emissions in various wavelength regions are strongly related, it is not quite clear why many of these relations are non-linear power-law relations.

1.1.3 Stars earlier than B3

Stars with spectral types earlier than B3 are known to be soft X-ray emitters (Seward et al. 1979; Harnden et al. 1979). The average X-ray luminosity $L_X$ of early-type stars is proportional to their bolometric luminosity, roughly $L_X \sim 10^{-7}L_{bol}$. (Pallavicini et al. 1981). This is a firm observational constraint on models for the heating mechanism operating in the atmospheres of these stars. The absence of a well-developed convection zone in the envelopes of early-type stars seems to exclude an interpretation by solar-like magnetic phenomena which create coronae such as found around late-type stars. A theoretical picture of what might be occurring in these stars was proposed by Lucy & White (1980), who argued that shocks in the radiatively driven winds of early-type stars can heat the wind enough to generate thermal X-rays. Stars with spectral types later than approximately B1 cannot generate strong, radiation-driven winds (Abbott 1979). Theory predicts that stellar winds become very weak towards later spectral types (Lucy 1982), which might explain why so few normal stars later than B3 (and earlier than $\sim$A8, see next subsection) have been detected in X-rays.
1.1.4 Late B-, A- and F-type stars

No convincing theory for the soft X-ray emission by stars with spectral types between approximately B3 and late-F has been advanced. The later types in this spectral range, later than about mid-A, appear to show an X-ray behaviour somewhat similar to that of stars of spectral types later than G0. However, observations of stars in this spectral range (mid-A to late-F) show a weaker dependence of activity on rotation (Topka et al. 1982; Walter 1983), and a relative decrease of X-ray detections towards earlier spectral types (Schmitt et al. 1985, and references therein). Because of high instrumental detection limits, it is not clear whether this decrease in detection rate is caused by a lower average activity level, or by a decrease in the number of stars which exhibit coronal activity.

Our knowledge of the soft X-ray behaviour of the earlier 'intermediate' spectral types (late-B to mid-A) is even more limited. Observations with Einstein suggest that the X-ray luminosities from the few detected stars (7) in this spectral range depend on the bolometric luminosity in the same way as the X-ray luminosities from stars with earlier spectral types, \( L_X \sim 10^{-7} L_{bol} \) (Pallavicini et al. 1981).

1.2 ROSAT

1.2.1 ROSAT's place in X-ray astronomy

Since the Earth's atmosphere absorbs X-ray photons, X-ray astronomy depends on instruments in space. The first observations were done with sounding rockets and high-altitude balloons in the early sixties. Sounding rockets carried instruments sensitive to relatively low-energy X-rays (0.25–10 keV), while balloon instruments only detected X-rays, with energies exceeding 20 keV (lower-energy X-rays cannot penetrate the atmosphere at the typical altitudes reached by these balloons, about 40 km). A review on X-ray missions is given by Bradt et al. (1992).

The first satellite dedicated entirely to X-ray astronomy was the UHURU satellite (1970–1973), sensitive in the range 2–20 keV. It provided the first all-sky X-ray view of the brightest (339) X-ray objects in the sky. With the Dutch satellite ANS (1974–1976), the physics of stellar coronae started by the detection of X-rays from two bright late-type stars (Mewe et al. 1975). The Einstein mission (HEAO-2; 1978–1981) resulted in a wealth of data on X-rays from 'normal' stars. Due to its relatively high sensitivity for faint sources at low photon energies (down to 0.1 keV), Einstein could detect the weak thermal X-ray emission from stellar coronae with temperatures down to \( \sim 1 \) MK (Vaiana et al. 1981). EXOSAT (1983–1986) contributed to the understanding of coronal emission by means of its relatively high spectral resolution (Turner et al. 1981).

The main goal of ROSAT (launched in 1990, and still operating) was to obtain for the first time a deep all-sky survey in soft X-rays (Trümper 1983). This enables statistical studies of complete samples of 'normal' stars in soft X-rays.

1.2.2 ROSAT All-Sky Survey

Three important questions in stellar X-ray astronomy, formulated in a review by Rosner et al. (1985), are still largely open: (i) What is the nature of the X-ray emission from stars of early spectral type? (ii) Do single giants of very late spectral type and supergiants
emit any X-rays? (iii) Do normal main-sequence stars in the spectral range approximately B5–A4 emit any X-rays?

Statistically complete samples can be drawn from the ROSAT All-Sky Survey. Analysis of the All-Sky Survey data, especially on detection rate, and level of X-ray emission, is expected to yield statistically significant answers to questions like (ii) and (iii) stated above. Comparing the survey data with smaller-scale surveys in other wavelength regions can give indications on the nature of X-ray emission in specific groups of stars (e.g., question (i) stated above). Since the exposure times during the survey are limited, pointed observations are required to reach the required sensitivity to comprehend the nature of the X-ray emission from early-type stars (spectral types earlier than ~B3) and in 'intermediate' type stars (between B3 and G0).

1.3 Summary of this thesis

The ROSAT All-Sky Survey, briefly described in Chapter 2, has resulted in a large amount of data. This thesis studies several stellar samples from this extensive data-set, in a joint project with the ROSAT team at the Max Planck Institut für Extraterrestrische Physik in Garching. The ROSAT soft X-ray observations have been combined with various optical observations, which I summarize per chapter, hereafter.

The All-Sky Survey, the PSPC instrument, and the data-analysis used in this thesis are described in Chapter 2. The conversion of count rates to X-ray fluxes requires an assumption about the X-ray spectrum of the source. Chapter 2 presents a tool to find the appropriate conversion factor, using the information contained in the observed spectral hardness ratio. Furthermore, Chapter 2 argues that the conventional method of model-fitting, using a \( \chi^2 \)-minimization, is not appropriate for ROSAT PSPC pulse height spectra. Instead, another method is proposed, which is based on the Poisson distribution of errors in these pulse height spectra.

Chapter 3 addresses some questions related to the previously noted tight relationship between chromospheric and coronal measures for radiative emission in late-type stars. For this purpose chromospheric Ca II H&K line-core observations have been obtained nearly simultaneously with ROSAT All-Sky survey observations for a sample of ~200 late-type stars. Although it may be expected that radiative signatures of presumably the same physical phenomenon (magnetic surface activity) are in some way related, there is no theoretical prediction of the exact form of this relationship, mainly because the heating mechanisms of the chromosphere and the corona, and the interaction between these two are still not understood. Observational constraints on the parameters defining this relationship are extremely useful in gaining a better understanding of the physical mechanisms for the radiative behaviour of the outer atmospheres of these stars. We show that the relationship between measures for radiative emission from the chromosphere and the corona is tightest, if normalized emissions (i.e., the amount of X-ray or chromospheric emission relative to the bolometric emission) are compared, instead of luminosities or surface flux densities. The normalized X-ray emission varies approximately quadratically with the normalized excess Ca II H&K line-core emission. This relationship appears to hold for dwarfs and giants of all spectral types from as early as F5 to late K. Furthermore, Chapter 3 shows that the X-ray spectra of giants are relatively hard compared to those of dwarfs of the same level of X-ray emission, up to surface flux densities of \( 10^6 \) erg sec\(^{-1}\) cm\(^{-2}\).
Dwarfs show an increasing X-ray spectral hardness (i.e., an increasing average coronal temperature) with increasing X-ray flux; giants do not show this correlation (Chapter 3 and 4).

Chapters 4 through 7 focus on the X-ray properties of a flux limited sample of \( \sim 180 \) bright main-sequence stars with spectral types between A8 and G2. The fundamental question addressed in Chapter 7 is whether all A8–G2 dwarfs emit X-rays, or only a fraction of them. A related question is: Do stars with earlier spectral types behave differently from stars with later spectral types, e.g., with respect to the activity-rotation relation?

Chapter 4 presents the results of the ROSAT All-Sky Survey observations and the Walraven 5-colour photometry, obtained for these stars. Values for the effective temperature, surface gravity and interstellar reddening are obtained from a comparison of the observed Walraven colours with theoretical values. These parameters are used to derive accurate X-ray surface flux densities.

In Chapter 5 a discussion is given of a combined Fourier-Bessel transformation technique, that is used to derive rotational velocities from spectral line profiles. We find that this technique is especially useful for the derivation of low rotational velocities (between 5 and \( \sim 20 \) km/sec). In Chapter 6 this method is applied to optical spectra of all sample stars. The range in derived rotational velocities is 5 to 100 km/sec. Velocities smaller than 5 km/sec or larger than 100 km/sec cannot be obtained, due to the limited spectral resolution and signal-to-noise ratio.

Chapter 7 combines the observations described in Chapters 4 and 6. In the activity-rotation behaviour of stars with spectral types earlier than \(~\)F7 we find evidence that the X-ray emission decreases towards earlier spectral types. We argue that the amount of activity-related radiative emission in cool dwarfs \((B - V) > 0.5\) relative to the total radiative emission, is prescribed by one parameter only: the rotation period scaled with a colour-dependent efficiency factor. We show that this efficiency factor resembles the convective turnover time for dwarfs, but is much smaller than the convective turnover time for giants. The dependence of activity on rotation disappears for warmer stars. We argue that both detections and upper limits are consistent with the hypothesis that all stars in our sample exhibit coronae.

Chapter 8 describes a search for white-dwarf companions to Oe- and Be-type stars. In order to be able to distinguish X-rays emitted by accretion onto a white dwarf from intrinsic X-rays from the Oe or Be star, and to distinguish the X-rays emitted by Oe and Be stars from intrinsic X-rays from ‘normal’ O and B stars, we studied the X-ray properties of all O and B stars brighter than \( V \sim 6.5 \). We find no indications for white-dwarf companions. The X-ray emission from O and early B stars is consistent with an origin from shock-heated radiatively driven winds. Oe and Be stars behave similar to ‘normal’ O and B stars, with respect to their level of X-ray emission and the detection rate as a function of spectral type.

References
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