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Memorie della

50 (38) years of stellar X-ray astronomy

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Abstract. Hot plasmas emit most of their radiative output at soft X-ray energies. The discovery of soft X-ray emission from our Sun was thus not really surprising, since the high temperature of the solar corona had previously been inferred from the correct interpretation of the observed forbidden line emission from a variety of highly ionized ions. The detection of X-ray emission from thousands of solar-like stars at X-ray luminosities substantially above the emission levels observed from the Sun was not anticipated and came as a real surprise. Systematic surveys of stellar X-ray emission among all stars located in the Hertzsprung-Russell diagram have demonstrated that the appearance of hot coronae is a universal phenomenon occurring in all cool stars with outer convection zones. When put in the stellar context, the Sun turns out to be a relatively inactive star due to its slow rotation and advanced age. Young and more rapidly rotating stars are ubiquitously found to exhibit much increased X-ray luminosities compared to the Sun, and this finding suggests that the high-energy environment of our Sun was quite different when it was young and when our solar system was formed, compared to the high-energy environment we encounter today.

Key words. Stars: activity, coronae; X-rays: stars

1. Introduction

The solar corona has been known to mankind for a very long time, ever since humans started observing the Sun during a total solar eclipse. At that time the Sun appears appears to be surrounded by some irregularly formed "crown", i.e., its corona, yet the true physical nature of the solar corona was only recognized in the forties of the last century, when optically observed coronal emission lines, previously erroneously attributed to a readily introduced new element "coronium", were identified by Grotrian and Edlen with forbidden transitions in highly ionized iron atoms such as Fe XIII and Fe XIV. The formation of such highly ionized ions through collisional ionization requires temperatures in excess of 1 MK, i.e., many orders of magnitude larger than the characteristic temperatures found in the solar photosphere. To explain this discrepancy in temperature some heating is required and the search for and identification of the heating mechanism(s) of the solar corona has become the holy grail of coronal physics.

As was realized and summarized for example by Elwert (1954), hot plasmas with temperatures in excess of 1 MK emit most of their radiative output at soft X-ray wavelengths either through continuum radiation mostly in the form of thermal bremsstrahlung or line radiation. However, this soft X-ray radiation is absorbed high up in the Earth's ionosphere

Send offprint requests to: J.H.M.M. Schmitt at altitudes of 110 km and above, and therefore a direct observational study of the solar (soft) X-ray emission required the availability of rocket technology, which became available after World War II. Indeed, the "expected" X-ray emission from the Sun was detected using Geiger counters Friedman et al. (1951).

While the solar X-ray flux is instrumental for the formation of the Earth's ionosphere, the overall energy losses of the Sun in the X-ray range are very small and amount to less than one part in a million of its whole energy budget. As a consequence, the extrapolation of the observed solar X-ray properties to stars at large led to rather pessimistic expectations as to the detectability of stellar coronae, although it is interesting to read R. Giacconi's Nobel address on this issue (Giacconi 2002). At any rate, not surprisingly, none of the first couple of hundreds extrasolar X-ray sources detected in the sixties and seventies of the last century were "normal", solar-like stars.

2. The discovery of stellar x-ray coronae

The (accidental) detection of X-ray emission from the RS CVn binary *Capella* by (Catura et al. 1975), using a proportional counter on board a sounding rocket, is usually considered to be the first X-ray detection of a stellar corona other than the Sun. Some handful or so of coronal sources had been detected (for a good summary of this early work see Mewe 1979), when the introduction of soft X-ray imaging into X-ray astronomy revolutionized both solar and, in particular, stellar X-ray astronomy. While the first X-ray images of the solar corona obtained with the soft X-ray telescope onboard *Skylab* (Vaiana et al. (1973), using film as detector !) showed the extreme complexity of the structure of the solar corona, the observations carried out with the *Einstein Observatory* – operated between 1978 and 1981 – and later with *EXOSAT* (1983 - 1985) and then *ROSAT* (1990 - 1998), have led to the discovery of X-ray emission from many thousands of stars similar to our Sun. Coronal X-ray sources have been studied with all major X-ray satellites, and at present, the large observatories *XMM-Newton* and *Chandra* allow X-ray observations of coronal sources with unprecedented sensitivity and spectral resolution.

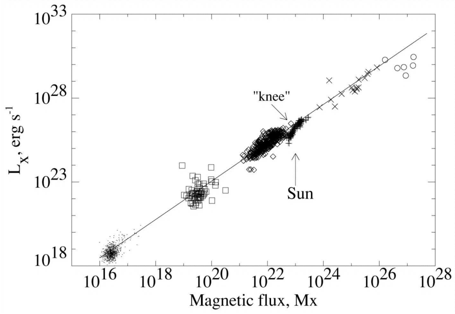

Fig. 1. X-ray luminosity vs. magnetic flux for quiet, active and flaring solar features and stars; taken from Pevtsov et al. (2003); the correlation between these quantities extends over more than ten orders of magnitude.

What makes X-ray mission particularly interesting as a physical diagnostics for stars appears is a correlation established between X-ray luminosity and magnetic flux; the association of solar coronal X-ray emission with magnetic fields had been known, ever since spatially resolved X-ray images of the Sun had been available. By studying quiet and active Sun features as well as active stars Pevtsov et al. (2003) established an almost linear relationship between observed X-ray luminosity and magnetic flux extending over 12 orders of magnitude (see Fig. 1). Thus, empirically X-ray emission appears to be a good proxy for magnetic fields or more precisely magnetic flux, a quantity that is very difficult to measure otherwise. Since the short-wavelength X-ray emission is not contaminated by any photospheric contribution, the detection of X-ray emission (for a solar-like star) is thus considered to be the cleanest proxy indicator for magnetic activity.

Fig. 1 is clear evidence for the magnetic character of coronal heating and solar activity in general. As such coronal phenomena in the Sun are linked to magnetic phenomena in the solar photosphere and in particular to the Sun spots, whose magnetic nature had been shown by Hale (1908) much earlier. On the other hand, polarity reversals of the solar magnetic field were only established in 1950ies of the last century, making the 11-year Sunspot cycle, originally discovered by Schwabe (1844), into a 22-year magnetic cycle. "Dynamo Theory" has become the preferred theoretical paradigm to explain the observed phenomenology of magnetic activity, and (differential) rotation and turbulence are the required ingredients for the so-called α-Ω-dynamos, which provide an explanation for the observed cyclic variations of solar and stellar activity.

3. X-ray emission from cool solar-like stars

The *Einstein Observatory* observations carried out between 1978 - 1981 were the first to demonstrate the wide-spread occurrence of X-ray emission from main sequence stars with outer convection zones (Vaiana et al. 1981). In particular, it appeared that that onset of outer convection as predicted by stellar structure theory is reflected by a rather vigorous onset of X-ray activity. This issue was studied by Schmitt et al. (1985), who found an large increase in detection rate when going from stars with $B - V \sim 0.2$ to stars with $B - V \sim 0.5$. Later, the large stellar samples available from ROSAT observations allowed a precise delineation of this so-called "onset of convection". Schröder & Schmitt (2007) studied the detection statistics among bright stars of spectral type B and A (i.e., stars without outer convection zones) to stars of spectral type F5 (i.e., stars with convection zones; cf., Fig.2), using the complete data from the ROSAT all-sky survey. While there is a "bottom" of about 15% of X-ray detections among A-type stars, the precise nature of which is subject of some debate, there is also a sharp increase in X-ray detections going from spectral type A7 to F2, precisely at that spectral type, where outer convection zones start develop, suggesting that stars with turbulent regions find it easier to produce X-ray emitting coronae. This finding is of course in line with the idea that magnetic dynamos operate in these outer convection zones and that it is the magnetic fields generated by these dynamos, which eventually cause cause the observed X-ray emission (see Fig.1).

What was left open by the *Einstein Observatory* observations was the question whether the X-ray emission for stars with outer convection was ubiquitous, i.e., whether X-ray emission is really found for **all** stars or whether there might possibly exist X-ray dark cool stars like our Sun. To put it differently, the observed range of activity as observed through X-ray emission could not be described. To this end Schmitt (1997) investigated complete

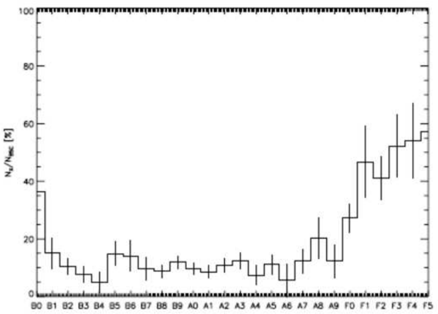

Fig. 2. Fractional detection rate in ROSAT all-sky survey of (apparently) bright stars ($m_V < 6.5$) vs. spectral type; taken from Schröder & Schmitt (2007). Note the sudden jump in detection rate at spectral type of F0-F2.

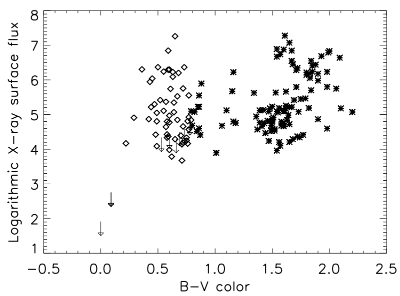

Fig. 3. Mean X-ray surface flux F_X vs. B-V color for complete samples of nearby stars of spectral type F through M; taken from Schmitt (1997); the mean X-ray surface fluxes extend over almost four orders of magnitude.

volume-limited samples of solar-like F and G dwarfs within 13 pc, K dwarfs within 10 pc and M dwarfs within 7 pc using data from both the ROSAT all-sky survey and ROSAT pointed observations. These samples are statistically meaningful and truly complete in the sense that all stars known within this volume were observed with sufficient sensitivity to detect solar-like X-ray emission levels (and even well below), while the coverage of the low-luminosity end of the X-ray luminosity distribution function had been rather limited with *Einstein Observatory* data. In Fig.3 the results of Schmitt (1997) are plotted in the form of mean X-ray surface flux F_X vs. absolute magnitude M_V for a complete sample of nearby stars. As is clear from Fig.3, none of the stars with absolute magnitude $M_V < 5$ was detected, while X-ray emission from **all** F-type stars was detected. Specifically, the detection rate for F-type stars is 100 %, the detection rate for G-stars is more than 85 %, with all the upper limits resulting from stars for which only survey data (and no more sensitive pointing data) were available. The conclusion from these studies must then be that coronal formation is indeed a **universal phenomenon** on solar-like stars. A corona containing hot plasma is always formed at the interface between a turbulent outer convection zone and space. Truly X-ray dark solar-like (main sequence) stars do not exist at least within the immediate solar environment and must be very rare if they exist at all.

4. The power of high-resolution x-ray spectroscopy

While the X-ray detectors used on board of the early X-ray missions such as the *Einstein Observatory* and *ROSAT* had little or even no energy resolution, the current generation of X-ray satellites provides the possibility of high-resolution X-ray spectroscopy with transmission (*Chandra*) or reflection (*XMM-Newton*) gratings. To demonstrate the power of X-ray grating spectroscopy I show in Fig.4 (taken from Ness et al. 2002) an exemplary set of X-ray spectra, covering an important diagnostic range with some of the strongest X-ray lines. Specifically a comparison of the

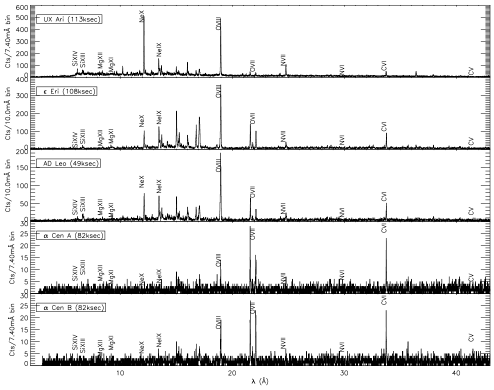

Fig. 4. *Chandra* LETGS spectra of the stars UX Ari, ϵ Eri, AD Leo, α Cen A and α Cen B and in the wavelength range from 5 - 45 Å, taken from Ness et al. (2002). Note the wealth of emission lines in this spectral range, which opens up many diagnostic possibilities.

Chandra LETGS spectra of the stars UX Ari, ϵ Eri, AD Leo, α Cen A and α Cen B and in the wavelength range from 5 - 45 Å is provided . This rather small sample of stars covers both quite active stars (UX Ari), an intermediate star (ϵ Eri) and a low-activity star (α Cen A). The X-ray spectra show a multitudes of emission lines from carbon, oxygen, nitrogen, neon, iron, magnesium and silicon, and even a casual inspection of the high-resolution spectra shows significant differences in the lines appearing in each object, best visible in the strengths of the Ne X (Lyα) line at 12.14 Å and the O VII and O VIII lines at 19 Å and 22 Å. It should be obvious that high-resolution spectra such as presented in Fig.4 can be utilized for detailed abundance, temperature and density diagnostics, and the quality of the now available stellar X-ray spectra rivals that of solar X-ray spectra.

5. Selected results

In the following I present some selected results of stellar X-ray astronomy in an attempt to cover the whole field, yet somewhat reflecting my own biases.

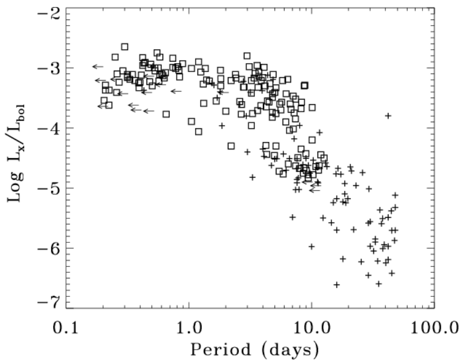

Fig. 5. X-ray (L_X) to bolometric luminosity L_{bol} vs. rotation period, taken from Pizzolato et al. (2003). Rapid rotators are found near the saturation level of 10^{-3}.

5.1. Rotation-activity relation

Fig.3 demonstrates that for (main sequence) stars of given spectral type and hence mass, X-ray luminosity, which is used as a measure of activity, can differ by almost four orders of magnitude. If activity is related to the operation of a magnetic dynamo in the stellar interior, which is the common paradigm of stellar activity, stellar rotation must also play an important role. A relationship between X-ray luminosity and stellar rotation was first discovered by Walter & Bowyer (1981) for RS CVn systems and for field stars by Pallavicini et al. (1981), and provided the context for numerous studies of the so-called "rotation-activity connection". The most extensive compilation of rotation and X-ray data for coronal sources is that of Pizzolato et al. (2003), who study a sample of a few hundred stars, for which both X-ray measurements as well as photometric rotational period measurements were available; their results are presented in Fig.5, where the ratio of X-ray (L_X) to bolometric luminosity L_{bol} is plotted vs. stellar rotation period. Rapid rotators with periods below ∼ 10 days are found near the so-called saturation level of $L_X/L_{bol} \sim 10^{-3}$, while the period activity relationship is found for the slower rotators. Thus active stars emit about one thousandth of their total energy output in the X-ray range; in contrast, early type stars without outer convection zones emit only a fraction of 10^{-7} at X-ray energies.

5.2. Young stars

According to the rotation-activity relation rapidly rotating objects tend to produce far more X-ray emission than slower rotators. Numerous studies of stellar rotation in young stellar clusters and associations have shown that young stars do indeed rotate very rapidly and, in consequence, they should up ubiquitously in X-ray surveys of such areas. X-rays surveys of young star clusters and star forming regions have indeed become a major study area for stellar astrophysics. By studying young solar-like stars, we essentially study the properties of the Sun in the early days of our solar system, since according to the rotation-activity paradigm, also the Sun in its youth was a rapid rotator with ensuing activity.

On top of the X-ray emission attributable to the increased magnetic activity of rapidly rotating young stars, additional X-ray production mechanism are encountered in very young stars. Is such star a complex inflow and outflow phenomena are observed, both of which appear to be accompanied by X-ray emission. The role of accretion will be discussed below(see Fig.7 and 9), the X-ray emission in those cases is thought to come from the bottom region of the accretion funnels, when the material, infalling with velocities of a few hundreds of km/sec, is stopped at the photospheric level. Also, in some young stars evidence for emission far away from the surface has been produced, the most beautiful example being the X-ray jet from the classical T Tauri star DG Tau, which I present in Fig.6 (cf., Güdel et al. 2011). In the case of DG Tau soft X-ray emission is observed from a extended region far away from the star, and precision studies with *Chandra* (Schneider & Schmitt 2008) allowed to trace back the jet emission to the immediate vicinity. While the number spatially resolved jet emission from young stellar objects (YSO) is small, such emission appears to be wide-spread and Güdel et al. (2007) suggest that the YSO X-ray sources showing a two-absorber X-ray (TAX) phenomenology represent spatially unresolved jet emission.

5.3. Temperature-activity relation

Already with the first stellar X-ray observations carried out using the *Einstein Observatory* a trend of "mean" X-ray temperature with X-ray luminosity was noted in the sense that the derived single-component X-ray temperatures or X-ray hardness ratios seemed to related to the total X-ray output. With high-resolution spectra these relations can be re-examined and far better quantified. In particular, one can use the measured O VII/O VIII-ratio (cf., Fig.7) as a measure of temperature and the sum of the O VII and O VIII-line fluxes as a measure of X-ray luminosity. These ions cover a wide range of temperatures and only for very hot plasmas (where oxygen is fully ionized) or rather cool plasmas (where oxygen is in ionization stages of O VI and below) flux is missed. It is instructive to consider the measured O VII/O VIII-ratio as a function of oxygen luminosity (see Fig.7), where we plot these data for main sequence stars as well as a sample of classical T Tauri stars (CTTS) and related objects; while for main sequence stars the two quantities are well correlated, demonstrating the earlier claimed temperature-activity relationship, Fig.7 also demonstrates the soft excess in and the peculiar character of the CTTS objects, supporting the view that additional X-ray production mechanisms are operating in those objects as also suggested by their anomalous O VII line strengths discussed in sec.5.4.

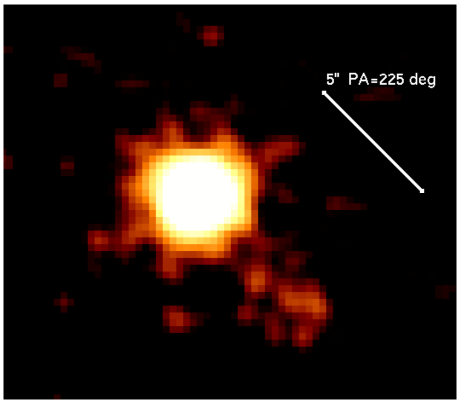

Fig. 6. *Chandra* soft X-ray image of DG Tau and its surroundings taken from (Güdel et al. 2011).

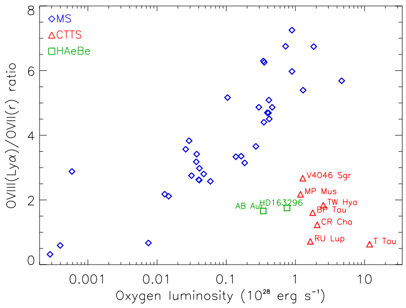

Fig. 7. OVIII/OVII line strength ratio vs. overall oxygen luminosity for main sequence stars (diamonds) and CTTS and related objects, where additional X-ray production mechanisms are thought to operate (taken from Robrade et al. 2007).

5.4. Coronal densities

The most widely used and most powerful diagnostics for measuring hot plasma densities has become the O VII triplet at ∼ 22 Å; the triplet consists of a resonance line at 21.6 Å , an intercombination line at 21.8 Å , and the so-called forbidden line at 22.1 Å. In a high-density plasma the forbidden level will be de-excited through collisions and therefore the forbidden line disappears. As example of measured O VII triplets I show in Figs.8 and 9 the observed triplets for the stars ϵ-Eri (taken with the *Chandra* Low Energy Transmission Grating (LETGS) and TW Hya (taken with the *XMM-Newton* Reflection Grating Spectrometer (RGS)). The difference in the observed strengths of the forbidden line at 22.1 Å is very obvious. TW Hya is an example of a CTTS star, i.e., a young star surrounded by an active accretion disk. The almost complete absence of forbidden O VII line emission in TW Hya indicates that at least the soft X-ray emission originates in a region of very high density Stelzer & Schmitt (2004) and seems to be a common property of CTTS, indicating that accretion provides a substantial contribution to the total soft X-ray output (Schmitt et al. 2005), while ϵ-Eri is an exam-

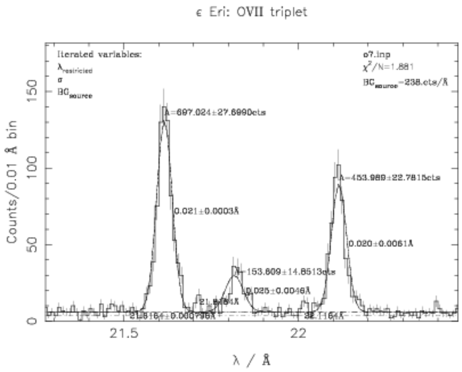

Fig. 8. OVII triplet region for the star ϵ-Eri (taken from Ness et al. 2002); note the strength of the forbidden line at 22.1 Å.

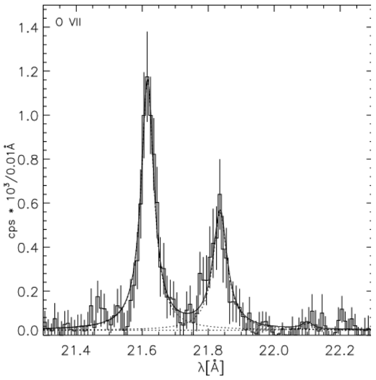

Fig. 9. OVII triplet region for the CTTS TW Hya (taken from Stelzer & Schmitt 2004); note the absence of the forbidden line at 22.1 Å.

ple of a star with quite modest activity not that much different from the Sun; it is, however, surrounded by a dust disk and harbors at least one planet.

5.5. Stellar flares

The X-ray emission observed from the Sun is not constant and found to be variable on many timescales. Specifically, many thousands of X-ray flares have been observed. In the strongest of such events on the order 10^{32} - 10^{33} erg are released. At the least the stronger ones of these solar flare events go together with the production of non-thermal X-ray emission and the production of energetic particles. On stars

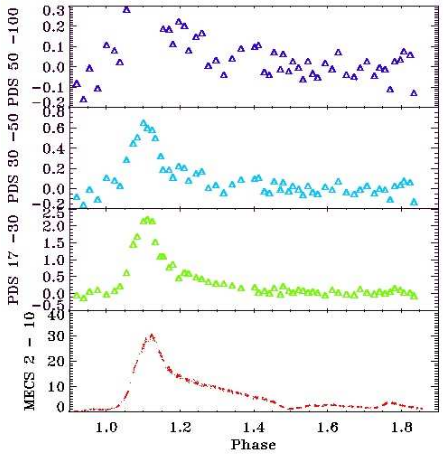

Fig. 10. *Beppo-SAX* light curve of giant flare on Algol in the energy bands 2-10 keV, 17-30 keV, 30-50 keV and 50 - 100 keV.

similar phenomena are observed; as a matter of fact, stellar X-ray flares can be more powerful by several orders of magnitude than the strongest solar flares ever observed, and by analogy one also expects nonthermal X-ray emission as well as particle generation. Unfortunately, the direct experimental demonstration of the occurrence of these phenomena in stars is difficult. On the Sun, non-thermal X-ray emission usually dominates the integrated emission at energies above $\approx$ 20 keV, however, at these energies the reflectivity of X-ray telescope is greatly diminished and consequently only non-imaging data with far inferior sensitivity are available.

A particularly well observed X-ray flare is that on Algol, observed with the *Beppo-SAX* satellite from 0.1 - 100 keV (cf., Schmitt & Favata 1999; Favata & Schmitt 1999). Algol is a binary system consisting out of an early type primary orbited by an evolved secondary with a period of 2.87 days. Because of synchronous rotation the secondary is a rapid rotator and the source of Algol's observed X-ray activity. The flare is outstanding because of its extremely large energy release exceeding 10^{37} erg at soft X-ray wavelengths and the fact that X-ray emission has been recorded up to 100 keV with the PDS instrument on board *Beppo-SAX*. The spectrally resolved light curves of this flares phased up with Algol's orbital phase are shown in Fig.10; a detailed analysis of the spectral energy distribution of this flare by Favata & Schmitt (1999) shows that the X-ray spectrum can be explained by a very hot thermal plasma without any non-thermal contributions. In this context it is worth mentioning that Algol is known as a source of non-thermal radio emission, however, in the X-ray range there is no need to invoke non-thermal emission components. The other remarkable feature in this flare is the dip in the light curve at phase $\phi = 1.5$, i.e., at a time when the X-ray dark primary component is located in front of the X-ray bright secondary component. From this eclipse and the fact that there is no self-occultation over a time scale significantly in excess of the half the orbital time geometrical constraints on the flaring volume can be derived.

6. Conclusions

Over the last decades stellar X-ray astronomy has become a vital part of X-ray astronomy at large. Just like cataclysmic variables, supernova remnants, neutron stars, quasars, clusters of galaxies and other types of sources solar-like stars are sources of X-ray emission that are being explored using the current generation of X-ray telescopes. X-ray studies of such objects allow us to infer properties the Sun had when its cycle had subsided during the Maunder Minimum and when it was very young. Furthermore, models used to interpret the solar corona can be used to interpret stellar X-ray emission and test to what extent the much more energetic phenomena observed on stars can be explained within the context of models devised in a solar context. In a more general context X-rays allows to study the outermost, hot regions of cool stars and characterize their physical properties.

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