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X-ray Emission from Isolated Be Stars

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Abstract.

I discuss the X-ray observations of Be stars, and how their properties compare to non-emission B stars. I focus on several specific stars that show high flux levels and variability but also report on several interesting survey results. The Be X-ray properties are discussed in the context of wind-shock X-ray emission from normal OB stars as well as in the context of general mechanisms that have been proposed to explain the Be phenomenon. Finally, I conclude with a discussion of the spectral diagnostics that will be available from the new generation of X-ray telescopes.

1. Introduction

The X-ray emission from single Be stars must be viewed in the context of OB star X-ray emission. The X-rays that are ubiquitous in O stars at a level of $L_x \sim 10^{-7} L_{Bol}$ are thought to come from shocks in the massive winds of these stars. The generally accepted shock mechanism is the line-force instability (Lucy & Solomon 1970; Owocki, Castor, & Rybicki 1988), which arises directly from the physics of line driving and leads to an abundance of spatial structure, even without any external perturbations.

In this paper I will explore the extent to which the X-ray properties of Be stars can understood in terms of the wind-shock emission that is invoked to explain the X-rays emitted by O and early B stars. I will contrast the observed X-ray emission from Be stars to that seen in non- emission B stars and focus on several specific stars. This paper will explore what constraints these observations can put on models of Be activity and also look forward to the new diagnostics that will be available with the next generation of X-ray telescopes.

2. X-rays from Hot Stars

The wind-shock paradigm has not been observationally tested in any great detail, as the only X-ray data available have been of very limited spectral resolution. Some general, phenomenological properties of OB star X-ray emission have been determined via both large surveys (primarily with *ROSAT*) and detailed measurements of a few stars with the higher resolution instruments *ASCA* and *EUVE*. In Table 1 I summarize the important properties of EUV and X-ray telescopes past, present, and future.

Table 1. X-ray and EUV Spectral Missions.

Mission	Launch	Spectral Range (keV)	Resolution ($\lambda/\Delta\lambda$)	Effective Area (cm^2)
Einstein	1978	0.4 - 4.0	2	100
ROSAT PSPC	1990	0.1 - 2.3	2	200
EUVE	1992	0.02 - 0.18	300	1
ASCA	1993	0.5 - 12	20	1000
RXTE PCA	1995	2 - 60	10	6500
Chandra gratings	1999	0.1 - 10	600	20
XMM RGS	2000	0.4 - 2	300	100

In several hot stars, X-ray emission lines have been measured, confirming the thermal nature of the emission. Measurements of the relative lack of attenuation of the soft[1] X-rays in several O stars (Cassinelli et al. 1981; Cassinelli & Swank 1983; Hillier et al. 1993) and the EUV in the B giant ϵ CMa (Cohen et al. 1996), as well as modeling of the O VI line in ζ Pup (MacFarlane et al. 1993) has shown that the X-ray emitting plasma in these stars must be spatially distributed throughout the stellar wind. Analyses of the spectral energy distributions in the low-resolution *Einstein* (Hillier et al. 1993) and *ROSAT* data (Cohen, Cassinelli, & MacFarlane 1997), and of specific emission line ratios in the higher-resolution *EUVE* data (Cohen et al. 1996), showed that in most hot stars the temperature distribution of X-ray emiting plasma is weighted toward less-hot material. The most detailed observations show that the vast majority of plasma has $T < 10^6$ K, and there is relatively little with $T > 5 \times 10^6$ K (Cohen et al. 1996).

The overall levels of X-ray emission imply that a small fraction of the wind mass is heated to high temperatures at any given time in O stars (Long & White 1980; Hillier et al. 1993; Owocki & Cohen 1999). However, for B stars, this filling factor of hot gas is larger, and for mid- and late-B stars it can exceed unity, assuming the theoretical mass-loss rates are correct (Berghofer & Schmitt 1994; Cohen et al. 1997). This presents a serious challenge to most wind-based models of X-ray production in these B stars. Of course, clumping of the wind can, in theory, alleviate this discrepancy because thermal X-ray emission scales as density-squared. However, prodigious amounts of clumping would be required in many cases, and keeping overdense material in the wind very hot is a difficult task.

Finally, there has been very little time-variability observed in the X-ray emission of early-type stars, especially when compared to observations of late-type stars. This observational fact implies that the emitting structures, whatever their origin, are either in a steady-state configuration, or are so numerous that their aggregate properties are constant.

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[1] In this paper, the term "soft X-ray" refers to X-rays with $h\nu < 1$ keV, roughly, while "hard X-ray" refers to $h\nu > 1$ keV.

This observational database is generally in qualitative agreement with the predictions of the line-force instability wind shocks in terms of temperature and spatial structure, at least for O and very early B stars. However, other models might also fit the limited data. There have, in fact, been quite a few models proposed for the production of X-rays in OB stars. These include alternate wind-shock models (Mullan 1984; MacFarlane & Cassinelli 1989; Porter & Drew 1995; Cranmer & Owocki 1996), magnetic/coronal models (Waldron 1984; Tout & Pringle 1995), and magnetic-wind hybrid models (Babel & Montmerle 1997a). Magnetic models are attractive because they are theoretically capable of producing the large observed emission measures. Some of these alternative scenarios might be especially applicable to Be stars.

There are several reasons why we might expect Be stars to have different X-ray properties than normal OB stars. The first is that Be stars tend to have denser and more variable winds than non-emission B stars. Because X-ray emission is proportional to density squared, a modest increase in mass-loss rate or a deviation from a smooth, spherically symmetric flow would lead to an increase the X-ray luminosity. The second reason that Be stars might be expected to have enhanced X-ray emission is the occurrence of non-radial pulsations (NRPs) in many of these objects. Such photospheric variability might lead to the formation of co-rotating interaction regions and associated shocks and X-ray emission. NRPs could also make the formation of clumps in the wind more likely.

If the Be phenomenon involves magnetic fields, these could provide an additional possible source of X-ray activity. There are currently no viable detailed models of coronal-type activity in Be stars, but if magnetic fields are present in some Be stars, this would at least suggest the possibility of magnetic heating and/or confinement. One model that has been applied to the purported magnetic rotator θ^1 Ori C is a magnetically confined wind, in which a radiation driven outflow is trapped in a closed magnetic loop, within which the flows that originate at the two foot-points are forced to collide at the top of the loop with a large relative velocity (Babel & Montmerle 1997a,b). It has recently been shown that at least one Be star, β Cep, has a large-scale magnetic field with a polarity that varies with the stellar rotation (Henrichs et al. 2000).

Finally, the presence of the Be disks themselves could be related to X-ray production, possibly in combination with any of the other general mechanisms already discussed, and perhaps intimately connected with the cause of the episodic mass-loss that appears to feed the Be disks. In any scenario in which the stellar wind feeds the disk, such as the wind compressed disk (WCD) model (Bjorkman & Cassinelli 1993), there is potential for X-ray emission at the wind-disk interface.

3. X-ray Data for Be Stars

3.1. Surveys

The *ROSAT All-sky Survey (RASS)* was used to search for white dwarf companions to Be stars, and as a byproduct compiled information about single Be stars (Meurs et al. 1992). The results of the survey indicated that the incidence of X-ray emission is lower in Be stars than in B stars (6 % vs. 16 %).

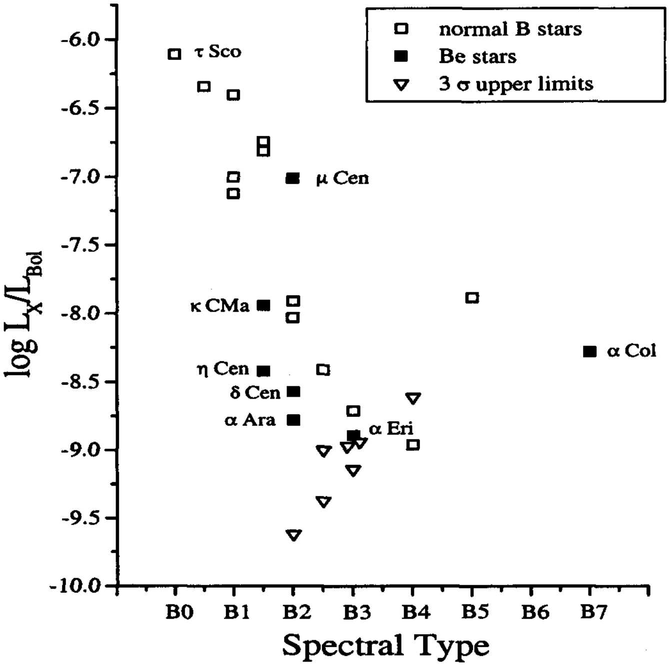

Figure 1. The trend of L_X/L_{Bol} with spectral subtype among B Stars.

However, because the *RASS* involved mostly very brief pointings, it detected only the brightest X-ray sources among hot stars (typical limiting luminosity of $L_X \approx 10^{30}$ ergs s^{-1}).

A much more sensitive survey of a smaller number of B stars was carried out using pointed *ROSAT PSPC* observations (Cohen et al. 1997). The limiting sensitivity in this survey was better than $L_X \approx 10^{28}$ ergs s^{-1}. Unlike the Meurs et al. (1992) study, in which any star having had $H\alpha$ in emission was called a Be star, the Cohen et al. (1997) determined the current Be status from recent literature. Cohen et al. detected all 7 of the Be stars but only 8 out of 15 non-emission Be stars of the same spectral types. In Figure 1 I show the L_X/L_{Bol} values the survey stars as a function of spectral type. In Figure 2 the cumulative L_X/L_{Bol} distributions of the Be and B stars are compared. The median value for Be stars is about three times higher than for the B stars.

3.2. Individual Stars

There are several interesting individual cases of Be star X-ray emission which I will discuss in this subsection. First, it should be mentioned that the unusual Be star γ Cas will not be discussed in detail. Its X-ray properties are so extreme as to not be applicable to the understanding of many other Be stars. As such, it probably deserves an entire article to itself, and, in any case, many of

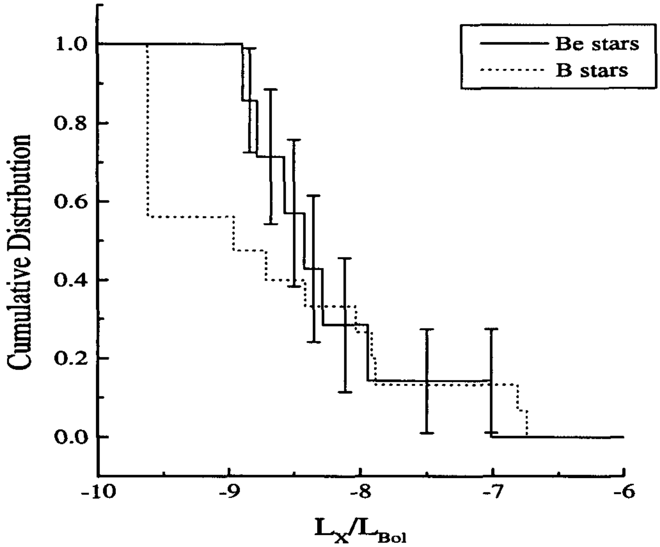

Figure 2. Cumulative L_X/L_{Bol} distributions of Be and B stars reconstructed from the pointed *ROSAT* observations using a Kaplan-Meier estimator implemented in the ASURV survival analysis package (Feigelson & Nelson 1985).

its properties are discussed by other authors at this conference (e.g. Smith & Robinson, these proc.).

In general, OB stars show remarkably constant X-ray emission, with only a handful of detections of time variability. As mentioned above, this is surprising in the context of wind shocks, as the growth and decay of individual shocks might be expected to lead to significant variability. A significant fraction of the small number of X-ray variable hot stars, however, are Be stars.

The B2 Ve star μ Cen is one of only two B stars out of the 27 in the *ROSAT* sample of Cohen et al. (1997) to show time variability. In Figure 3 observations are shown that were taken during four orbits, spanning about two days. There is a strong indication of variability on timescales of more than 1000 s, but little firm evidence for variability on shorter timescales. These data were taken during 1993, when the optical emission activity of the star was on the increase. However, this *ROSAT* observation was *not* made during an outburst, according to the NRP ephemeris (Rivinius et al. 1998).

The higher X-ray flux observed at the beginning of the *ROSAT* observation of μ Cen was due almost entirely to an excess in the hard band ($h\nu > 0.5$ keV). In fact, the spectral energy distribution of this star over the entire duration of the observation is relatively hard. Only τ Sco and ξ^1 CMa have harder *ROSAT* spectra among the 27 B stars observed by Cohen et al. (1997).

The most significant X-ray variability observed in any hot star was the large X-ray flare in λ Eri (B2 IIIe), which lasted slightly less than 1 day, and represented a seven-fold increase in the *ROSAT PSPC* count rate (Smith et al.

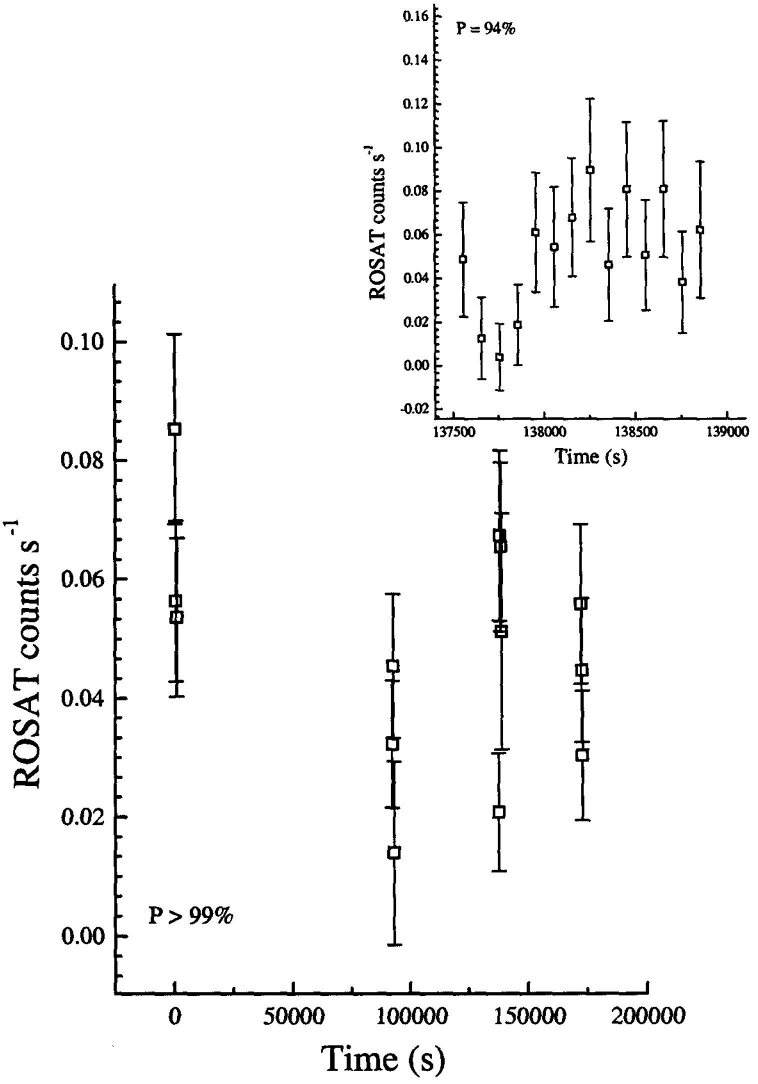

Figure 3. *ROSAT PSPC* count rate for μ Cen. Each data point represents about 400 s. The hypothesis of a constant source can be rejected at better than the 99 % level for the observation as a whole. The data within each individual orbit, however, is relatively constant, with the most significant variability seen in the data from the third orbit (inset), for which the constant-source hypothesis can be rejected at the 94 % level.

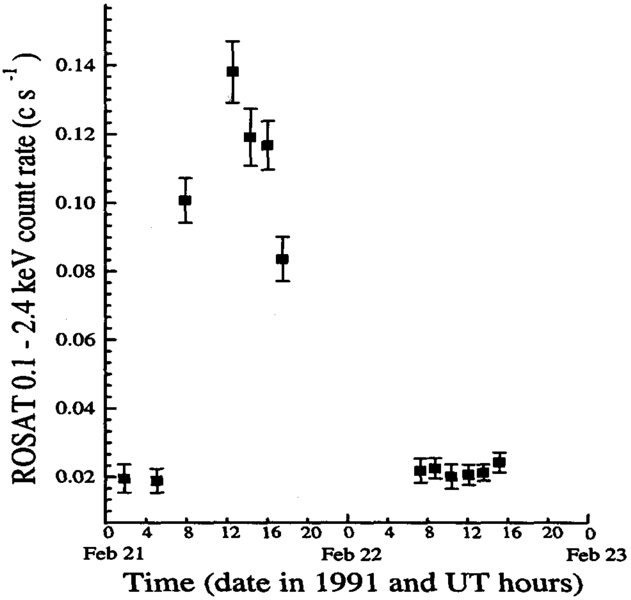

Figure 4. *ROSAT PSPC* X-ray light curve for λ Eri (from Smith et al. 1993, used with permission).

1993). The total fluence in this event was in excess of 10^{36} ergs, making it the largest stellar X-ray flare ever detected (see Figure 4). As in μ Cen, the increase in the X-ray flux is attributable almost entirely to the hard *ROSAT* band. Smith et al. (1997) have also found evidence for dense, temporary structures above the photosphere of this star. Combined with the hard spectral response of the X-ray event, these data provide a picture of a Be star with surface magnetic fields and associated magnetic heating.

The prototype β Cephei variable, β Cep (B1 IIIe), which also shows Hα emission, is another Be star that has X-ray variability. The level of variability is low, but it is periodic, and is modulated on the same period as the optical variability associated with its NRPs (Cohen, Finley, & Cassinelli 2000). This relationship between NRPs and photospheric variability on the one hand, and presumably wind-related X-ray activity on the other, is one of the strongest indications yet of a direct photosphere-wind connection in hot stars. Furthermore, it is evidence that pulsations in hot stars can affect the circumstellar environment and the X-ray emission in these objects. The phased X-ray lightcurve is shown in Figure 5.

The variability of the X-ray emission of β Cep may not be directly associated with its status as a Be star, as Cohen et al. (2000) find evidence for similar variability in 3 other β Cephei variables, none of which are Be stars. It should be noted that the time coverage of the *ROSAT* observation of this star is exceptionally good, and it is certainly possible that more OB stars would have modest X-ray variability detected if they could be observed for 20,000 s, as β

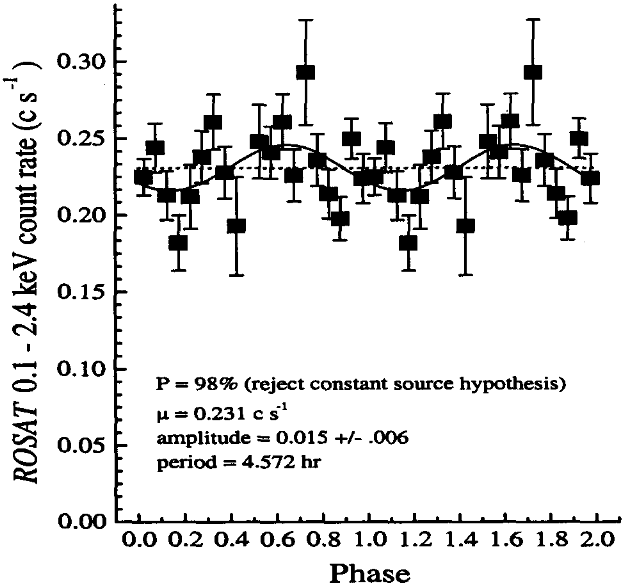

Figure 5. *ROSAT PSPC* X-ray light curve for β Cep, folded on the 4.572 hour primary optical period. The hypothesis of a constant source can be rejected at the 98 % confidence level.

Cep was. It should also be noted that while this observation was long, it was not long enough to detect modulation on the 12 day period over which the magnetic field, recently detected by Henrichs et al. (2000), has been found to vary.

Finally, I will briefly mention τ Sco (B0 V), which has been suggested to be a Be star with a weak disk seen pole-on (Waters et al. 1993). However, it now seems that the observed Brackett emission lines can be better explained by a non-LTE effect at the base of the wind, rather than by a disk (Waters, these proc.). The X-ray properties of this star are relevant, however, because they show that certain hot stars have X-ray emission that simply cannot be explained by the standard line-force instability wind shock mechanism. The X-ray emission from τ Sco is so hard that a significant quantity of plasma with temperatures in excess of 20 million K must be present on this star (Cohen, Cassinelli, & Waldron 1997). This might be due to magnetic activity or magnetically confined winds. The presence of a magnetic field on this hot star is plausible due to its extreme youth (Kilian 1992). Alternatively, the hard X-rays might be produced by an interaction between dense, infalling blobs (seen in red-shifted O VI absorption), and the fast stellar wind (Howk et al. 2000).

4. Constraints on Be Star Models Provided by the X-ray Data

Based on the available X-ray database of OB stars, it can be concluded that the X-ray properties of Be stars are not very different than those of B stars in general. Their X-ray luminosities may be somewhat higher (Cohen et al. 1997 suggest a factor of three, but their sample may not be completely unbiased). And there are several interesting cases of stronger, harder, and more time-variable X-rays from Be stars. However, it should be kept in mind that the existing data are relatively sparse, with only about 25 isolated Be stars detected with X-ray telescopes over the past two decades, and with very few of these observations having durations in excess of 5000 s.

To the extent that Be stars are moderately more X-ray-active than non-emission B stars, there are several possible causes. The higher luminosities could be due to the higher mass-loss rates that Be stars have compared to B stars of the same spectral subtype (Grady, Bjorkman, & Snow 1987). Alternately, the Be X-rays could be due to wind shocks that are enhanced compared to those in B star winds, perhaps by additional clumping, driving at the base via NRPs, or by interactions with corotating interaction regions or with the Be disks.

The time-variable X-ray fluxes and high X-ray temperatures seen in μ Cen and λ Eri, among other stars, have several possible implications. The time variability may be indicative of magnetic flaring (more likely in the case of λ Eri, in which the X-ray outburst was large) or of emission from an ensemble of wind shocks that is dominated by a small number of shock zones. The high X-ray temperatures (in τ Sco, but also in the X-ray enhancements seen in λ Eri and μ Cen) may also be indicative of magnetic activity, or hybrid magnetic-wind activity. Alternately, they could be due to shocks involving the winds of these Be stars interacting with slow, dense (or even infalling) clumps or with the disk.

The presence of disks around Be stars might be expected to affect the X-ray properties of these objects via interactions with the stellar wind. In the WCD model, or any other model in which wind material directly feeds a disk, the wind is decelerated across a shock as it enters the disk. Specific models of the wind compressed disk predict shock temperatures of several hundred thousand degrees Kelvin, with somewhat higher temperatures in stars rotating at close to the break-up velocity (Bjorkman & Cassinelli 1993). If Be disks have an inner radius (*i.e.* they are detached from the stellar surface) then there may also be shock emission where the wind impacts the inner edge of the disk. Additionally, there may be infall of material from a disk that cannot be rotationally supported, and this material may interact either with the wind or the photosphere itself, leading to shocked plasma and X-ray emission.

If large quantities of shocked plasma do exist at the disk-wind interfaces, then the shocks must be relatively weak, and the temperatures correspondingly low. One might ask how much "warm" plasma ($T \approx 10^5$ K) could be present on Be stars and still be consistent with the X-ray data. In Figure 6 I show several emission models convolved with the *ROSAT PSPC* spectral response matrix. It can be seen from this figure that even a huge amount of $T = 2 \times 10^5$ K plasma could not be reliably detected with *ROSAT* in the presence of the emission from a typical quantity of $T = 2 \times 10^6$ K plasma. However, $T = 4 \times 10^5$ K plasma would be detectable. A shock temperature of $T = 2 \times 10^5$ K corresponds to a shock jump velocity of 120 km s^{-1}, which is quite typical of the predictions of the oblique shocks on the surface of WCD disks (Bjorkman & Cassinelli 1993). So, as Figure 6 indicates, large quantities of shocked gas could exist at the wind-disk interface without *ROSAT* being able to detect it.

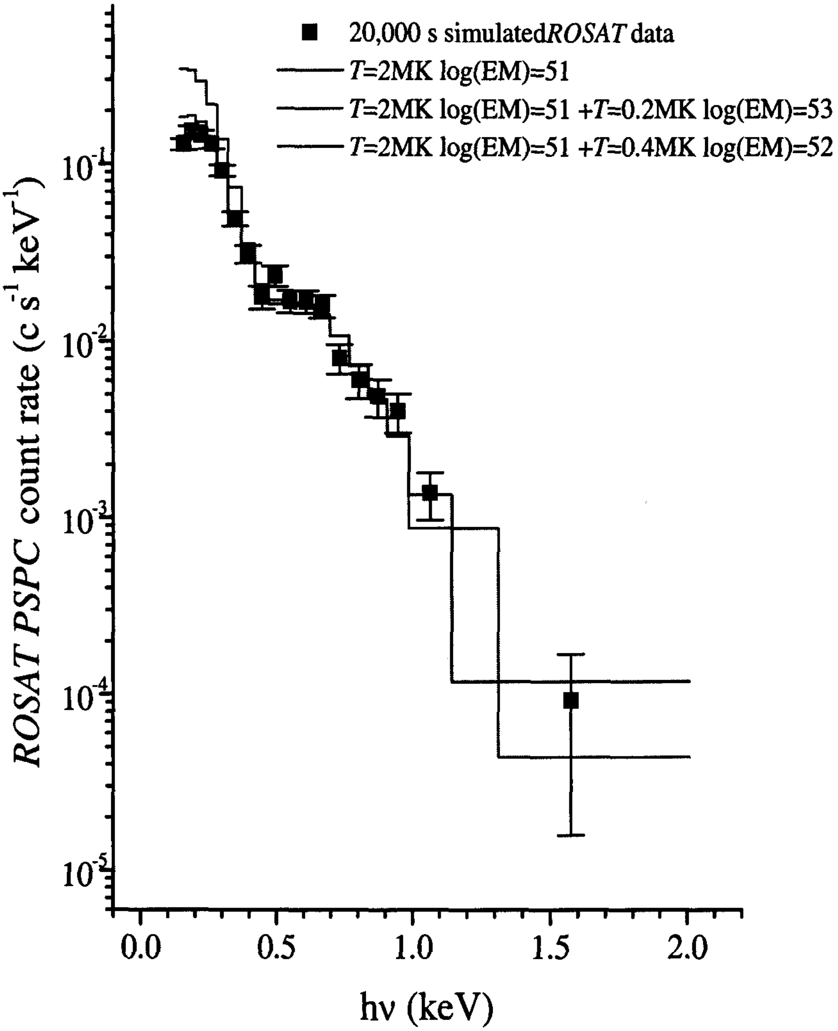

Figure 6. Three models at the resolution of the *ROSAT PSPC*, along with a simulated data set generated from the isothermal, $T = 2 \times 10^6$ K, model (points with error bars). The three models include the isothermal two million degree K model with an emission measure of 10^{51} cm^{-3}, which is thought to be representative of B stars, as well as two additional models that include a two million degree component but also have cooler components: one with a $T = 2 \times 10^5$ K component with 100 times the emission measure as the hotter component, and one with a $T = 4 \times 10^5$ K component with 10 times the emission measure.

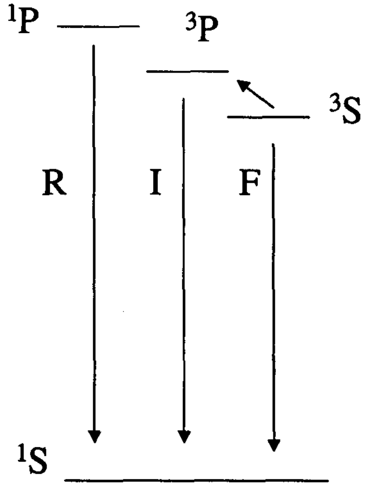

Figure 7. Schematic energy level diagram for a helium-like ion. The resonance (R), intercombination (I), and forbidden (F) transitions are indicated. Above some critical density (which increases with atomic number) collisions become efficient at transferring electrons from the triplet S level to the triplet P level, causing the intercombination line to strengthen at the expense of the forbidden line.

5. Prospects for Future Missions

The current X-ray missions have provided a modest amount of information about the flux levels and time variability properties of hot stars, including Be stars. However, their very limited spectral resolution has prevented any quantitative X-ray spectral diagnostics of Be stars from being employed. This situation will change shortly with the deployment of the next generation of X-ray telescopes: *Chandra*, *XMM*, and *ASTRO-E*, which have spectral resolutions approaching $\lambda/\Delta\lambda \approx 1000$. With this resolution, numerous individual X-ray lines will be measurable, and if they are wind broadened, they may even be resolvable.

High-resolution measurements of X-ray lines (and continua) will make possible the application of various spectral diagnostics. These include density- and temperature-sensitive line ratios, thermal versus non-thermal emission, deviations from equilibrium, Doppler shifts due to bulk motion, line opacity effects, and ionization balance via inner-shell X-ray transitions (fluorescence and resonant absorption).

One specific diagnostic with a lot of potential to discriminate among the various models for X-ray production in Be stars is the helium-like forbidden-to-intercombination line strength ratio, which is density sensitive. This physics behind this diagnostic is demonstrated schematically in Figure 7. This density diagnostic can be applied to helium-like ions from many elements, with each element having a somewhat different density- and temperature-sensitivity. For example, helium-like carbon exists at temperatures of about 3×10^5 K, and can diagnose densities of about $n_e = 10^9$ cm^{-3}, while helium-like silicon exists at temperatures near 3×10^6 K and its forbidden/intercombination line ratio is sensitive to densities near 3×10^{13} cm^{-3}. Using these line ratios to diagnose the density of the X- ray emitting plasma in Be stars will provide information about whether this hot plasma exists in the stellar wind, the disk, or even near the photosphere. Furthermore, density information combined with an emission measure determination gives information about the volume of the emitting structures. These data will put some very stringent constraints on the high-energy mechanisms operating in Be stars.

Another potentially useful X-ray spectral diagnostic involves probing the Be disks in Be/X-ray binaries with the hard X-rays from the compact companion. Accretion onto the compact object in these systems yields a hard X-ray continuum spectrum. If the compact object can be viewed while it is behind the Be disk, then an absorption line spectrum will be seen. The useful property of inner- shell X-ray absorption is that each ionization state leads to a single absorption feature, with the energy of each feature monotonically increasing with ionization level. Therefore, a small section of the X-ray spectrum can provide information about all possible ionization stages of an element such as silicon, or iron, in the disk.

6. Conclusions

Data, primarily from *ROSAT*, indicates that X-ray activity may be modestly stronger in Be stars than in non-emission B stars, but it is qualitatively not that different. There are, however, a subset of Be stars in which X-ray activity is quite strong and/or time variable. Taken together, these observational facts may indicate that the Be phenomenon has a high-energy aspect that can lead to enhanced X-ray emission, at least at some times and in some stars. Some objects (λ Eri, for example) have X-ray properties that simply cannot be understood in terms of the standard picture of wind shocks.

The long *ROSAT* observation of β Cep (and of three other β Cephei stars) indicates that pulsations can have an effect on X-ray production in hot stars, although the specific mechanism that connects these two phenomena is open for debate. As of now, however, no Be stars (save β Cep) have X-ray data with sufficient time coverage to draw any conclusions about the modulation of X-rays by pulsations.

The next generation of X-ray telescopes has the potential to vastly increase our understanding of the high-energy physical processes that occur on Be stars. This can be accomplished through the application of spectral diagnostics that are, for the most part, standard techniques in the UV, optical, and IR, but have not been applied in the X-ray due to the low spectral resolution of current instruments.

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Discussion

R. Ignace: Are the somewhat higher L_X values of Be stars over B stars consistent with Be winds having slightly larger mass-loss rates, as you alluded to (*i.e.* the X-rays are primarily from the polar wind, and do not arise in the disk)?

D. Cohen: Yes, this would be the most conservative explanation for the majority of Be stars.

H. Henrichs: Did all pulsating B stars in your sample show variable X-ray emission?

D. Cohen: Yes, β Cru and ξ^1 CMa at $> 3\sigma$, and β Cep and α Lup at just below the 3σ level.

C. Aerts: You observe X-ray variability in the hot β Cephei stars, but not in α Lup, which is cooler. You should check if this is a general conclusion. Also, β Cru is an eccentric binary in which the pulsation behavior seems to change between apastron and periastron. So it would be interesting to know if the X-ray luminosity is different at these two times.

D. Cohen: Well, α Lup is marginally variable in our *ROSAT* data. Also, I agree that it would be interesting to re-examine β Cru at different orbital phases. It is an interesting object, from an X-ray point of view.

A. Tarasov: X-ray photometry can be useful for finding hidden hot subdwarfs in these systems. In this case you can see some extra emission even in cool (B2 - B5) stars.

D. Cohen: Yes, but with the very poor spectral resolution of *ROSAT*, and the inherently soft X-ray emission of the B/Be stars themselves, this is a practical impossibility. But, with future high spectral resolution missions, it should certainly be possible to detect subdwarf companions.

M. Smith: You mentioned that for the possibly two good cases for X-ray variability (λ Eri and possibly μ Cen), it may be that these two stars are also unusual in having slightly more optical line profile variability than most other Be stars. So, I may be going slightly out on a limb in saying by conjecturing that the higher activities in these stars in both the optical and X-ray regions *might* be related. Also, note that the "flare" temperature of the 1991 X-ray event in λ Eri was several times hotter as well as being several times brighter. This may indeed be a qualitatively different characteristic which would add to the challenge of modeling it with even a non-standard wind-shock model.

D. Cohen: Regarding your first point, yes, simultaneous X-ray and optical (and ideally UV) observations would be very nice. On the second point, I would agree, but also point out that something that produces a transient increase in the X-ray flux by almost an order of magnitude is likely to also have a different spectral signature than the basal X-ray emission. For example, the infall of a dense clump interacting with the outflowing stellar wind would increase the X-ray flux levels, but it would likely also produce a higher X-ray temperature than the standard wind shocks.