X-ray and gamma-ray emission from single and binary early-type stars

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Abstract: Since their launch, both the *Chandra* and *XMM-Newton* satellites have provided us with a new and more detailed view of the high energy processes in massive stars. This paper reviews recent X-ray observations of a range of massive stars, both O-stars and Wolf-Rayet (W-R) stars, as well as both single early-type stars and binary systems, where colliding winds may well play a role. Results from high spectral resolution X-ray data will be reviewed, where the velocity structure of the individual line profiles can be resolved. Recent *INTEGRAL* gamma-ray observations of massive stars will be covered, as well as discussing the expected gamma-ray properties of early-type stars.

1 Introduction: massive stars

Massive stars are clearly important objects within a galaxy, impacting their environments via their radiation fields and dense, supersonic winds, and then via subsequent supernova explosions. Within our own galaxy there are many examples of early type stars, both single objects, binary stars and within young star clusters, such as NGC 3603. In many starburst galaxies there are very large numbers of young stars, which via the mass and energy injection from their stellar winds, can power the starburst phenomenon and drive strong superwinds out of the galaxy.

In this paper, the focus is on the high energy view of massive stars, particularly X-ray and gamma-ray emission from single and binary early-type stars, including both OB-stars and W-R stars. A complimentary review on the high energy emission seen from young stars in clusters is given by Montmerle (this proceedings).

The most obvious characteristics of OB and W-R stars are that they are massive, very luminous and have strong radiatively driven winds. It is these winds that allow early-type stars to interact directly with their environments and the observed high energy emission is directly associated with these winds as well.

The typical values for early-type stars winds are as follows: the winds are highly supersonic, with $v_\infty \sim 1000-3000$ km s^{-1}, and have mass-loss rates ($\dot{M}$) in the range of $\dot{M} \sim 10^{-7} - 10^{-4}$ M$_\odot$ yr^{-1}, with the more luminous stars having more massive winds. If we convert these numbers into typical kinetic energies, we find that $L_{wind} = 0.5\dot{M}v_\infty^2 \sim 10^{35} - 10^{38}$ erg s^{-1}. This should be contrasted with the bolometric luminosities, $L_{bol} \sim 10^{37} - 10^{40}$ erg s^{-1}. This means that the kinetic energy in the stellar wind is only a relatively small fraction of the total energy output of the stars (typically only 1% or so), but it is nonetheless very important. The stellar winds of the most massive stars can result in a very significant degree of mass-loss (the most massive stars lose most of their mass via their stellar winds during their lifetime), with a major impact on evolution. We also know that massive stars are very often in binary systems with other massive stars (and often in triple or quadruple systems). The periods of these binaries range from a couple of days up to many years (or hundreds or thousands of years). The presence of two massive stars leads directly to the phenomenon of colliding stellar winds. Colliding stellar winds in early type binary systems are now recognised as an integral part of our understanding of hot stars. Signatures of colliding winds have been found at virtually all wavelengths, and in a variety of guises, ranging from X-ray emission directly from the shocked region, to IR emission from dust formation inferred to be a consequence of wind collision.

There have been several important recent missions that are impacting on our understanding of high energy emission from massive stars. At X-ray energies, the *Chandra* and *XMM-Newton* X-ray satellites were both launched in 1999 and are both still operating. These two satellites both have high resolution grating instruments, which give unprecedented levels of spectral resolution at X-ray energies, allowing significant velocity resolution of the X-ray emitting material. The spectral resolution of these instruments is a few hundred km s^{-1}, which compares favourably with the terminal velocities of these objects. In this paper the focus is more on the high resolution observations of X-ray line emission, rather than the broad-band continuum properties of early-type stars, these observations yielding greater insight into the dynamics of the winds. At gamma-ray energies, the *INTEGRAL* satellite was launched in 2003, and is sensitive to the hard X-ray and low energy gamma-ray region.

This paper is organized as follows: Section 2 reviews the observed X-ray emission from single OB and W-R stars, and the various attempts to model the X-ray line emission. Section 3 reviews the situation for X-ray emission from binary early type stars, and colliding stellar winds. Section 4 covers results from gamma-ray observations from the *INTEGRAL* satellite, and Section 5 concludes.

2 X-ray emission from single OB and W-R stars

X-ray emission from early-type stars was first detected by the *EINSTEIN* satellite in the late 1970's. This discovery was rather unexpected and the details of what causes the emission remains a subject of debate. The two main proposals were that the X-ray emission was either caused by substantial "base corona" or that the X-ray emission was distributed throughout the wind (Cassinelli & Swank 1983). The lack of substantial low energy X-ray absorption was interpreted as being evidence against the base corona model, and the distributed emission model is preferred nowadays.

The basic observational facts for OB stars are as follows. The X-ray luminosities are typically in the range of $L_X \sim 10^{30} - 10^{34}$ erg s^{-1}. The X-ray luminosity of the early-type stars scales with bolometric luminosity, with a rough scaling of $L_X \sim 10^{-7} L_{bol}$. This scaling applies for O stars down into the early B-stars. For stars of later spectral types the scaling is rather flatter and for these stars the X-ray emission comes (at least in part) from unresolved companions (such as white dwarfs and low-mass stars that emit coronal X-rays). The general behaviour of the X-ray emission form early-type stars is illustrated in Fig. 1, which is taken from Berghöfer et al. (1997), using data from the *ROSAT* satellite.

The X-ray spectra of early-type stars are usually reasonably soft. Because they are not usually very strong X-ray emitters, the spectra are usually fitted with one or two temperature thermal models. In many cases, the softer component has a temperature of $kT \sim 0.5$ keV. In a number of cases, particularly with higher quality spectra there is also a harder emission

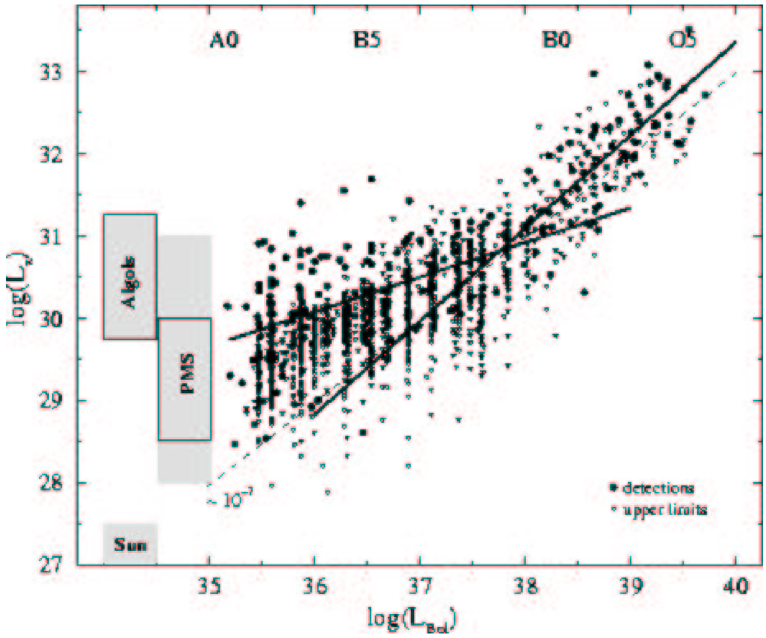

Figure 1: The X-ray luminosity (L_X) plotted against bolometric luminosity (L_{bol}), taken from Berghöfer et al. (1997). The solid lines represent regression lines for $L_{bol} \leq 10^{38}$ erg s^{-1} and $L_{bol} > 10^{38}$ erg s^{-1}. The dashed line shows $L_X = 10^{-7} L_{bol}$. The grey bars at the left side show typical ranges for the X-ray luminosity of Algol-type systems, pre-main sequence stars (PMS), as well as for the Sun.

component, with $kT \sim 2$ keV. There is some evidence for excess X-ray emission from (some) massive binary systems and this has been interpreted as being due to colliding stellar winds in such binary systems (see Section 4).

Radiatively driven winds are believed to be highly unstable, and the basic structure is expected to be punctuated by a whole host of shocks internal to the wind. These internal shocks will produce X-rays (Owocki, Castor & Rybicki 1988). Multiple shocks can also produce non-thermal particles and non-thermal radio and gamma-ray emission

In terms of the expected X-ray spectra from shocked heated gas, it will consist of continuum from thermal bremsstrahlung, but with strong contributions from line emission from the abundant atomic species, such as O, Ne, Mg, Si, S and Fe. The emission lines will come from predominantly hydrogen and helium-like ions of these elements. In contrast to this, non-thermal X-ray emission (from shock accelerated electrons for instance) will likely have a characteristic power-law shape. In reality, the emission from a given early-type star (single or binary) will have both thermal and non-thermal components (as we expect shocks to give rise to both forms of emission), and the thermal emission will certainly not be isothermal and will come from a range of different temperatures. Disentangling all these components from spectra with relatively few counts is rather challenging.

In addition to emission processes, absorption processes will also play a major role in the observed spectrum, as the abundant metals in the wind are very efficient at absorbing soft X-rays. For example, if we consider X-ray emitting material moving out in the wind of an O-star. From the point of view of the observer, material out in the wind on the far side of the star will be red-shifted and more heavily absorbed, and material on the near side will be blue-shifted and less heavily absorbed. This suggests that, for a spherical expanding wind, the resulting line profiles will be shifted towards the blue (with the red portions being more highly absorbed).

As mentioned earlier, one of the big advances in this field has been the launch of the *Chandra* and *XMM-Newton* satellites. The spectral resolution of the grating instruments on these satellites are around a few 100 km s^{-1}. With this resolution we are able to spectrally resolve the velocity structure of the emission lines in the X-ray spectra of early-type stars, and to gain new insights into the wind dynamics.

To return to the canonical result that $L_X \sim 10^{-7} L_{bol}$. We might expect the X-ray emission to scale as the wind density squared (the emission being due to free-free emission). This means that, as $\rho \propto \dot{M}/v_\infty$ for spherically symmetric winds, and as $\dot{M} \propto L_{bol}^{1.7}$ (Howarth & Prinja 1989), we might expect $L_X \propto L_{bol}^{3.4}$. This is obviously much steeper than observed, but we should also expect absorption to play a role, with an additional factor with $L_X \propto \exp(-c\tau)$ with c a constant and the optical depth $\tau \propto \dot{M}$. One explanation is that this absorption factor transforms the much steeper relationship for intrinsic X-ray emission into the observed linear relation. This seems rather contrived and is probably not the real explanation. Consequently, even this apparently very simple observed relationship for early-type stellar X-ray emission is not fully understood. What is clear is that the form of this relationship is a consequence of contributions from both emission and absorption (for soft X-rays, the $\tau \sim 1$ optical depth occurs at several stellar radii).

Interestingly, for OB stars in one young star cluster, namely NGC 6231 an even tighter relationship is seen. In this case all of the stars are at the same age and metallicity and this may be a clue as to what affects the relationship (Sana et al. 2005).

2.1 High resolution X-ray observations of single OB stars

Quite a number of single OB stars have now been observed with the *Chandra* and *XMM-Newton* grating instruments, and some examples and general results are discussed here. All the observed OB stars show Doppler broadened X-ray emission lines, from a range of highly ionized species. For example, Zeta Pup (an O4f star) shows strongly broadened and blue-shifted emission line profiles. The *Chandra* grating spectrum of Zeta Pup is shown in Fig. 2 (Cassinelli et al. 2001), with data from both the high energy (HEG) and medium energy (MEG) gratings. As can be seen, the spectrum is dominated by line emission from a range of (mostly) hydrogen- and helium-like ions. The line widths are typically around 850 km s^{-1} HWHM for Zeta Pup. In contrast to this, Delta Ori (O9.5 II) shows X-ray line profiles that are narrower, symmetric and largely unshifted (Miller et al. 2002), though the lines are still relatively broad (around 430 km s^{-1} HWHM, though this is much lower than the terminal wind velocity of 2000 km s^{-1}). As another example, moving to later type stars, Tau Sco (B0.2 V) has rather narrow lines (Cohen et al. 2003; Mewe et al. 2003). Tau Sco has a rather weak wind, certainly compared to Zeta Pup, which has a wind with a mass-loss rate around two orders of magnitude greater. This means that we can see deeper into the wind of Tau Sco.

As another example, multi-epoch X-ray observations of θ^1 Ori C (O5.5V) suggests that in this case we are seeing a magnetically confined wind. This star is both very young and shows evidence of being strongly magnetized (Gagné et al. 2005).

Typically, the observed X-ray lines are broader at shorter wavelengths, that is for lower ionization species and narrower for higher ionization species. This suggests that the X-ray emitting portions of the winds are cooler at greater distances from the star, where the wind is at higher velocities (and so the emission lines are broader). It is also clear from this that the observed X-ray emission comes from a range of radii (and densities). Interestingly, Tau Sco is an exception to this to this trend, with a rather weak trend in the opposite direction.

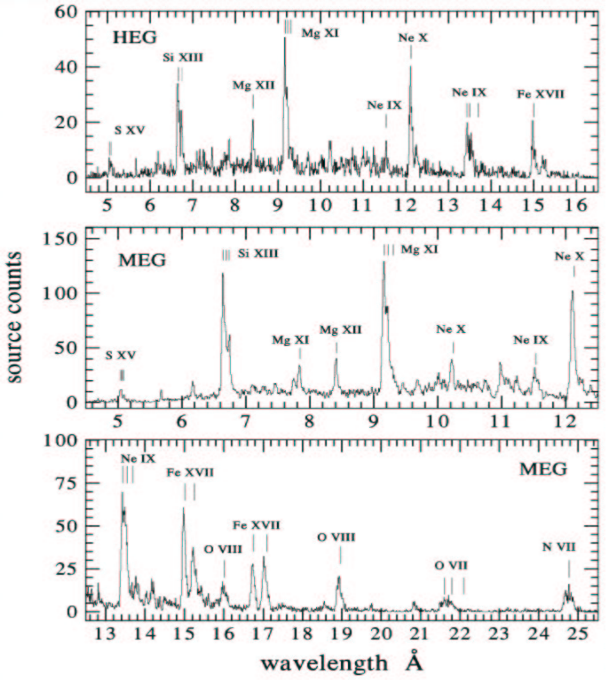

Figure 2: The *Chandra* spectrum of Zeta Pup, from Cassinelli et al. (2001), with data from HETGS HEG (top panel) and MEG (bottom panels). The ions responsible for the strongest emission lines are identified.

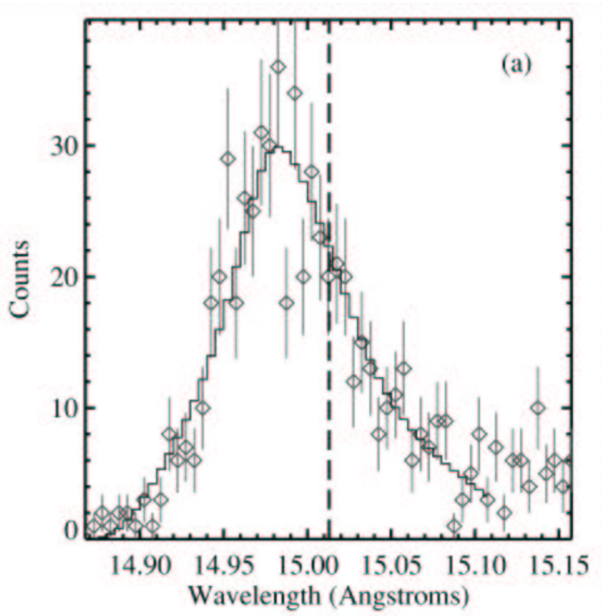

Figure 3: An example of the observed line profile and line fit, from the modelling work of Kramer et al. (2003). This is a fit to the Fe XVII line of Zeta Pup at 15.01Å, showing the broad blue-shifted profile.

2.2 X-ray line-profile modelling of single OB stars

Several different groups have attempted to model the observed line profiles from single OB stars. For example, one approach models the line emission using a highly structured wind model (Feldmeier et al. 2003; Oskinova et al. 2004), with many shocks. The X-rays come from the post-shock regions behind these shocks, and the X-rays suffer absorption by the underlying stellar wind and also from dense shells associated with the shocks (which can be rather opaque). Obviously in this model, red-shifted material, on the far side of the star, is more likely to be absorbed (having a longer path to traverse through the wind). This model is capable of reproducing the Zeta Oph emission lines.

Another approach have been adopted by Kramer et al. (2003). This is a simple phenomenological model, based on assumed distribution of X-ray material. The X-ray emitting material is assumed to be distributed throughout the wind, with the emissivity of the material given by a power-law distribution. The model also assumed an inner radius for the X-ray emission. Absorption by the stellar wind is also included, and this model is capable of reproducing the observed Zeta Pup emission lines, and implying that the X-ray emitting material extends well down into the inner regions of the wind. An example of the best fit to a Zeta Pup emission line from the modelling of Kramer et al. (2003) is shown in Fig. 3.

The message from this section is that there are several different approaches available to model the emission lines from OB stars. While these techniques are capable of well modelling the emission lines from some of the stars they are not capable of modelling all of the emission lines in a physically interesting way that yields new insight into the observed behaviour of these objects.

2.3 X-rays from single W-R stars

W-R stars, like OB stars, have radiatively driven winds, and given that W-R wind terminal velocities are comparable (or often greater) to those of O-stars we would expect single W-R stars also to be moderate X-ray emitters. One difference is that W-R stars tend to have substantially higher mass-loss rates than OB stars (implying higher levels of absorption).

While some W-R stars are strong X-ray emitters, those that are are usually binary systems, such as WR140 or Gamma Vel, it is true that some that are strong X-ray emitters are not always obviously binary systems. Here WR25 is an example (Raassen et al. 2003), and in this case it is strongly suspected that WR25 is a long-period binary system, possibly observed face-on.

In contrast to the binary W-R stars, there is less evidence of substantial X-ray emission from single W-R stars, particularly the WC subclass. For example, consider the WC W-R star WR114 (classified as a WC5). Oskinova et al. (2003) reported no detection of this star in a 16 ksec *XMM-Newton* observation, which implies $L_X < 4 \times 10^{-9} L_{bol}$. In contrast, Ignace et al. (2003) reported on *XMM-Newton* observations of WR1 (spectral type WN4) and did detect the system, with $L_X \sim 2 \times 10^{32}$ erg s^{-1}, slightly above the canonical L_X/L_{bol} value.

For the WN stars, the situation is rather unclear. For example, the WN8 star WR40 (HD 96548), which is considered a likely single star, has been observed with *XMM-Newton* by Gosset et al. (2004), and no detection was reported, conservatively implying $L_X < 2.6 \times 10^{-8} L_{bol}$. WR40 (and WN8 stars in general) has a relatively slow and dense wind, with $v_\infty <$ 1000 km s^{-1}. Such a situation makes the absorbing column in the wind greater (as well as probably reducing the likely X-ray emission).

In summary, no single WC W-R star has been unambiguously detected in X-rays. The reason for this is unclear. It could be that the driving mechanism for W-R star winds is markedly different, and so the internal wind structure is different, lacking the shocks that are present in the winds of OB stars. Other possibilities include the lack of emission being due to the enhanced mass-loss rate of the winds (which means more of the X-ray emission is self-absorbed by the wind). Following from this, WC W-R wind material is much better at absorbing soft X-rays than solar abundance material, which may well help this effect.

3 X-ray emission from binary OB and W-R stars: colliding stellar winds

In a binary system consisting of a W-R and an OB star, the two stellar wind will collide at high velocities. This means that the observed X-ray emission may well have more than one component, the two individual winds, and the wind-wind collision region. In many systems it is likely that the wind-wind collision region dominates the X-ray emission. This also means that we would expect to see substantial X-ray orbital variability as the wind-wind collision region moves around the orbit (both due to varying absorption and changing separation for eccentric systems).

In addition to the X-ray emission, non-thermal radio emission is another important tracer of the wind-wind interaction. Shocks produce non-thermal electrons which in turn will produce synchrotron emission. To illustrate this, Dougherty & Williams (2000) studied 23 W-R stars at radio wavelengths. Of these 9 are clear non-thermal radio emitters. Of these 9 objects, 7 are definite binaries and the other 2 possible binaries. It seems to be the case that non-thermal radio emission implies binarity. However, the converse is not necessarily true. Some known binaries do not have any non-thermal emission, and have simple thermal radio spectra. These tend to be the short period binary systems, and in these case the wind-wind collision region is buried deep within radio photosphere (and so any non-thermal emission is absorbed by the wind).

As an illustration, WR147 (spectral type WN8, with an OB companion) shows complex radio emission, with spatially separated thermal and non-thermal components. The radio components are separated by ~ 0.6 arcseconds. The thermal radio emission is associated with the wind of the W-R star, and the non-thermal radio emission is associated with the wind-wind collision (Williams et al. 1997).

We also expect X-ray emission from wind-wind collision and the two stars, and this system has been observed using the *Chandra* HRC instrument, which has a spatial resolution of 0.5 arcseconds. *Chandra* HRC observations show extended X-ray emission, centred on the wind-wind interaction zone, but also with emission from the W-R star (Pittard et al. 2002).

Returning to the grating instruments, the high spectral resolution means that we can, in principle, probe the dynamics of the wind-wind collision region. In addition we can do some more detailed physics from the line ratios of certain species. For example, helium-like lines have a triplet form, consisting of forbidden, intercombination and resonance ($f-i-r$) lines. The upper level of the f line is depopulated by electron collisions and/or UV photoexcitation, which means that the ratio $R = f/i$ is a diagnostic of wind density and UV field. Also, the mechanisms for populating the upper levels of the r, i and f lines have different temperature dependencies, which means that the ratio $G = (f+i)/r$ is a diagnostic of electron temperature.

3.1 Gamma Velorum: a colliding wind case study

As an illustration of high spectral resolution X-ray observations for colliding wind binary systems, here we look at results from a *Chandra* observation of the W-R binary Gamma Vel. Gamma Vel is the nearest W-R star (located at a distance of ~ 260 pc, although the distance is still the subject of some dispute and a higher value may also be possible), and consists of a W-R and an O-star of spectral types WC8+O7.5 (de Marco & Schmutz 1999). The system has an orbital period of $P_{orb} = 78.5$ days, with a moderate eccentricity of $e = 0.33$. The proximity of this system (and relative X-ray brightness) makes it a key object.

From a series of *ROSAT* observations, the system displays highly variable X-ray emission and is substantially brighter when the O-star is in front of the W-R star (Willis et al. 1995). This is broadly to be expected, as at this orientation, the emission from the wind-wind collision region will suffer much less absorption than at phases when the wind-wind collision region is behind the W-R star (the W-R star having the larger mass-loss rate).

The *Chandra* observation was taken during the X-ray "high state", with the O-star in front of the W-R star (see Fig. 4), and the results have been discussed in Henley et al. (2005) and Skinner et al. (2001). The main results are that the observed lines are generally unshifted, and have a mean FWHM of 1200 km s^{-1}. In addition, there is no correlation between measured line width and ionization potential or wavelength.

As has been discussed earlier, using high resolution line spectra, the $f-i-r$ triplets from He-like ions can be used to estimate the physical conditions. For example, the upper level of the forbidden line depopulated by electron collisions and/or UV photoexcitation and the ratio, $R = f/i$ is a diagnostic of n_e and UV field, which in turn can place constraints on location of the emitting plasma.

From the analysis of the $f-i-r$ line ratios for Gamma Vel, it seems likely that the Mg XI line originates closer to the O-star than the Si XIII. Given the respective excitation energies of these lines, we would expect this to be the other way round. We expect the hottest gas in

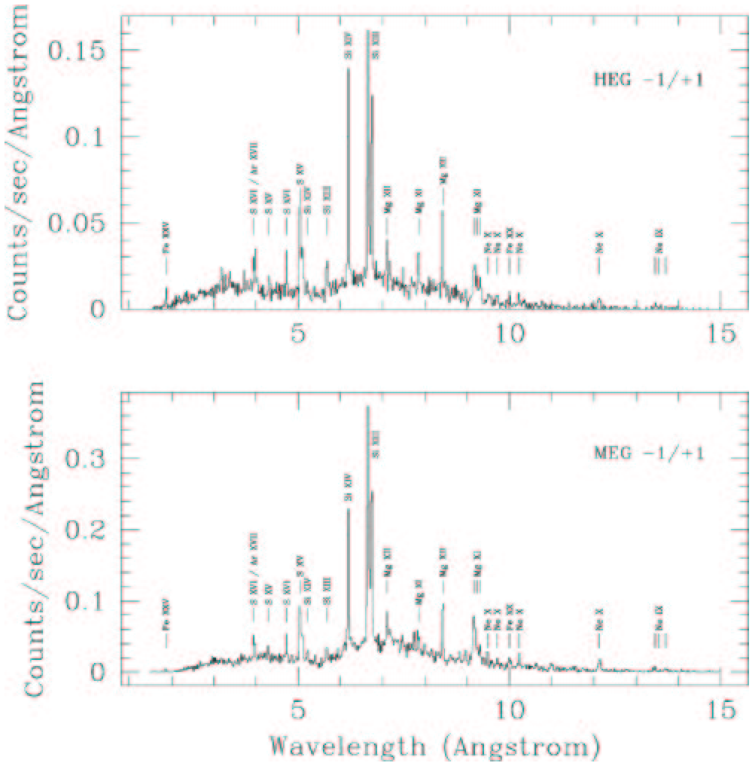

Figure 4: The *Chandra* Gamma Vel spectrum from Henley et al. (2005), showing data from both the high energy (HEG) and medium energy (MEG) gratings.

the system to be located near the line of centres of the system, with the temperature falling away from this point. The fact that we see things the other way round may be an indication of non-equilibrium ionization.

In addition, Schild et al. (2004) have reported on *XMM-Newton* observations of Gamma Vel, with one observation when the O-star is in front ("high state") and another when the O-star was behind ("low state"). Using spectral modelling of these two observations, to obtain the absorbing column, it is possible, along with estimates of the mass-loss rate, to place simple constraints on the 'clumping' factor of the wind. For Gamma Vel, Schild et al. (2004) derive a value of ~ 16, implying a rather highly clumped wind.

For the *Chandra* results, the emission lines were generally unshifted. This is rather unexpected, given the orientation of the system at the time of the observations, and the likely location of the shock surface (with unequal mass -loss rates). One possible explanation is that the shock cone in Gamma Vel is much wider than expected from basic wind parameters. A possible explanation for this wider shock is due to sudden radiative braking, as has been discussed by Gayley, Owocki & Cranmer (1997). In this scenario, the radiation field of the O-star can inhibit and decelerate the dominant wind of the W-R star. This in turn can quite substantially alter the location of the interface between the two winds, and results in a much wider shock angle. This is a result expected from theory, and these observations of Gamma Vel provide some evidence for the process at work.

Other colliding wind systems that have been well studied at X-ray energies with grating instruments include WR140 (Pollock et al. 2005) and Eta Car (Corcoran et al. in preparation). In these systems there are hints at some other physical effects at work - such as a substantial fraction of the wind kinetic energy going into proton acceleration rather than being thermalized in the shock (this is also seen in supernova remnants). This process can explain the narrower than expected X-ray emission lines, and needs to be considered in more detail.

4 Gamma-ray emission from OB and W-R stars

Although X-ray emission from OB and W-R stars is now an established field, gamma-ray emission from early type stars is still in its infancy and awaiting the first unambiguous detection. There has been speculation about possible gamma-ray sources associated with massive stars, for example, possible correlations between unidentified high energy *CGRO* EGRET sources and early-type stars have been noted (Benaglia et al. 2001; Benaglia & Romero 2003), though these connections are certainly not unambiguous. The eventual detection of gamma-rays will provide some useful insights into the shock acceleration processes in these stars.

There are several different ways that early-type stars can generate gamma-ray emission, mostly related to shock accelerated particles (and often with binarity). Inverse Compton (IC) emission is the most likely to be the dominant emission mechanism. Shock accelerated electrons interact with the strong UV radiation fields of both stars to generate gamma-ray emission. This process is believed to generate a power-law spectrum and is likely to be the dominant emission mechanism at hard X-rays and gamma-rays from massive stars.

There are other gamma-ray emission mechanisms, such as pion decay, relativistic bremsstrahlung, and emission from the decay of radioactive ^{26}Al, which may be important in other contexts or in harder energy bands. For instance, the ^{26}Al emission is a result of stellar nucleosynthesis in W-R stars, followed by the subsequent distribution of the material via the strong stellar winds. This emission is diffuse in nature, but is concentrated on regions of recent star-formation (as the radioactive decay timescale for the ^{26}Al is comparable to the lifetimes of massive stars).

The recently launched *INTEGRAL* satellite has further opened up the possibility of detecting hot stars at softer gamma-ray energies. As part of a program to detect such emission we have used the *INTEGRAL* satellite to observe the Cygnus region, including three nearby W-R stars, namely WR140, WR146 and WR147. These three stars are expected to be some of the brightest gamma-ray emitters, amongst the early-type stars without compact companions.

Unfortunately, in spite of a long exposure time (and the detection of massive stars with a compact companion, such as Cyg X-1 and Cyg X-3), there has been no detection of these sources, and we still await a confirmed gamma-ray detection of a massive star. This is disappointing, but the upper limits will provide some useful constraints on the emission processes in these colliding wind systems.

5 Summary and conclusions

We have reviewed recent results on high energy emission from both single and binary massive stars. Although a convincing detection at gamma-ray energies is still lacking, some more constrained upper-limits are now being derived on the gamma-ray emission.

At X-ray energies, there has been substantial progress, with many new *Chandra* and *XMM-Newton* observations of single stars and binary stars. For the single stars, some patterns are beginning to emerge, but it is clear that there are differences in the X-ray line-profiles, with some stars having lines that are blue-shifted, other that are not, and some marked differences in line width. These may well be explained (in part) by differences in the mass-loss rates of the winds (and the resulting wind optical depths).

For the binary systems, we also now have some phase resolved observations of colliding stellar winds. For some systems, the simple colliding wind models work reasonably well, while for others there are some major discrepancies. These observations are pointing towards some clear deficiencies in the current state-of-the-art models, such as in the complex radiation hydrodynamics, non-thermal ionization effects and the possibility of a substantial amount of the wind energy going into non-thermal acceleration of particles and not into thermal emission.

It is clear that both more observations of a wider variety of systems and with better phase coverage and enhanced models are required to move the field forward.

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