# A NEW PARADIGM FOR X-RAYS FROM HOT STARS

**A. M. T. Pollock**[1] **and A. J. J. Raassen**[2]

[1]ESA *XMM-Newton* Science Operations Centre, 28080 Madrid, Spain
[2]SRON, 3584 CA Utrecht, The Netherlands

## ABSTRACT

*XMM-Newton* observations of $\zeta$ Orionis suggest a new interpretation of the X-ray spectra of hot stars. The broad, slightly asymmetric lines all have the same velocity profile and probably originate in collisionless shocks behind which the exchange of energy between ions and electrons is so slow that electrons keep cool. The spectrum is excited instead by protons.

Key words: X-rays; OB stars; winds; shock waves.

## 1. SHAPE OF THE X-RAY LINES IN $\zeta$ ORIONIS

The nearby O9.7 Ib supergiant $\zeta$ Orionis was observed with the *Chandra* high-energy gratings by Waldron & Cassinelli (2001), who argued that at least some of the X-rays originate very close to the stellar surface at the base of the powerful wind that is a ubiquitous feature of such hot stars. Its X-ray spectrum has proved to be typical of those seen from O stars. Miller et al. (2002) commented on the little understood broad line widths and tried to reconcile the data with the popular view that shocks developing from instabilities in the wind line-driving mechanism are responsible for generating the X-rays.

*XMM-Newton* is ideal for observing such hot stars. The bandwidth of the Reflection Grating Spectrometer (RGS) matches perfectly that part of the X-ray spectrum in which the lines occur, extending the *Chandra* spectra to the C VI line near 34Å and beyond. The RGS resolves the lines and its high sensitivity allows the accumulation of enough statistics to study line profiles in detail. The RGS spectrum taken on 2002-09-15 is shown in Fig. 1. Where they overlap, the RGS and HETG spectra were essentially identical. In common with other O stars, the continuum was weak or absent.

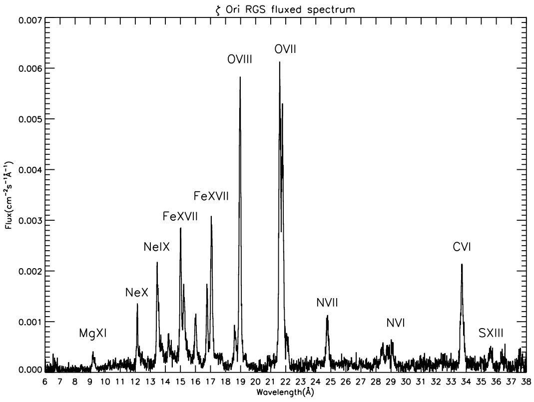

*Figure 1. The RGS spectrum of $\zeta$ Orionis on 2002-09-15.*

Comparison, for example, of the Ly$\alpha$ lines of C VI $\lambda 33.734$ and Ne X $\lambda 12.132$ separated by nearly a factor of 3 in wavelength shows their shapes in velocity space were indistinguishable. We have been able to synthesize a good fit to the entire spectrum with the same velocity profile for every line using a triangular line-profile model characterized by three parameters: independent red and blue velocities where the profile goes to zero and a central velocity shift from the laboratory wavelength. The best-fit parameters reported in Table 1 were calculated for a combined fit all the available *XMM-Newton* and *Chandra* grating spectra, which were taken over two years apart but agree well both in the shapes of the lines and in overall luminosity to within a few percent. The line-profile fits show some asymmetry in $\zeta$ Orionis's lines with the line centre blue-shifted by about $-300\mathrm{km\ s}^{-1}$ with similar blue and red widths about 70 to $80\%$ of the terminal velocity of $v_\infty = 2100\mathrm{km\,s}^{-1}$.

## 2. SHOCKS IN O-STAR WINDS

The general physical principles that govern the development of shocks (Zel'dovich & Raizer, 2002) were considered recently by Pollock et al. (2005) for the binary-

| | | |
|---|---|---|
| blueV | $-1585\pm25$ | $\mathrm{km\,s^{-1}}$ |
| centralV | $-303\pm31$ | $\mathrm{km\,s^{-1}}$ |
| redV | $+1723\pm30$ | $\mathrm{km\,s^{-1}}$ |

*Table 1. Best-fit line velocity parameters for the simultaneous fit to all the lines in XMM-Newton and Chandra grating spectra of $\zeta$ Orionis.*

system colliding-wind X-ray shocks in WR140. Similar considerations for single hot stars lead to some interesting conclusions. An O-star wind is a plasma flow in which particle interactions are long-range Coulomb collisions with particularly slow energy exchange between ions and electrons. The ion-ion collisional mean-free path is $l_{\mathrm{i-i}} \sim 7.0 \times 10^{18} {v_8}^4/n_{\mathrm{i}}$ cm (Spitzer 1962) where $n_{\mathrm{i}}$ is the ion density and $v = v_8 \times 1000\mathrm{km\,s^{-1}}$. Close to the photosphere of $\zeta$ Orionis, where the density is high and the velocity low, $l_{\mathrm{i-i}}$ is small, but then increases rapidly with radius. At about $3R_*$ above the stellar surface in the heart of the acceleration zone, $l_{\mathrm{i-i}} \approx 0.1R_*$ while at $10R_*$, $l_{\mathrm{i-i}} \approx R_*$. If strong shocks are to develop at all then some dissipation mechanism other than collisions must operate. Collisionless shocks (e.g. Draine & McKee 1993) are probably involved in which ions are heated to high temperatures while electrons remain cold. Any subsequent equilibration takes place downstream through energy exchange between ions and electrons though this happens slowly on a length scale of many stellar radii. The low X-ray luminosities of O-stars show that only a small fraction of wind material is involved, the vast bulk of which remains cool. It seems likely, then, that shocked gas will not survive for long before it is mixed back with cool material and disappears from view, leaving no chance for electrons to contribute to X-ray line or continuum emission. It is further likely that the X-ray plasma is far from equilibrium.

## 3. ORIGIN OF THE X-RAY LINES

In the absence of shock-heated electrons, protons in the immediate post-shock gas are probably responsible for exciting the X-ray spectrum. Through the shock transition, the ionization balance is unchanged although ions characteristic of the cool wind immediately find themselves in a hostile environment in which encounters take place with other ions at relative velocities of the same order as the the terminal velocity of $v_\infty = 2100$ km s$^{-1}$ in $\zeta$ Orionis. Protons of such velocities are an effective agent for ionization and excitation because the cross-sections depend on the relative velocity of the incident ionizing particle and that of the bound electron, whose order of magnitude is fixed by the Bohr velocity $v_{\mathrm{Bohr}} = 2188\ \mathrm{km\,s^{-1}}$. We suggest that it is the coincidence of this microscopic atomic value and the macroscopic terminal velocities of $\zeta$ Orionis and other O stars, that is the basic physical reason for the production of X-rays in hot stars.

Efforts made so far to account for the shape of the X-ray lines (e.g. Ignace & Gayley, 2002) have assumed that the emitting ions are moving with the majority cool gas, so that the red wing of the lines arises in material on the far side of the star flowing away from the observer. It is more likely that the line velocity profiles simply reflect instead the line-of-sight component of the thermalized motion of ions in the immediate post-shock gas. For a Maxwellian distribution, $\mathrm{HWHM}(v_{\mathrm{x}}) = \sqrt{2\ln 2(kT_{\mathrm{S}}/m)} = (\sqrt{6\ln 2}/4)v \sim 0.51v$. The observed lines in $\zeta$ Orionis are roughly consistent with this scheme, showing half-widths of about $75\%$ of the value of $0.51v_\infty$.

## 4. OTHER CONSIDERATIONS

In contrast to either ionization by electron impact or photoionization, which together account for the majority of observed X-ray plasmas, single O-star spectra may be one of the clearest examples of a protoionized plasma. The term “protoionized” seems appropriate both for the contrast with photoionized and because it describes the very earliest stages of post-shock ionization through which many plasmas are bound to pass before electrons are hot enough to take over ionization and excitation. The shock transitions themselves, though probably smaller in physical extent than those in colliding-wind flows such as WR140, obey similar jump conditions. The distinction between spectra rather lies in the post-shock relaxation layer, in the amount of equilibration that takes place between ions and electrons. If the hot plasma is confined by magnetic fields, as in WR140, for example, relaxation may take its course allowing energy to be transferred from ions to electrons, which may then excite a familiar plasma spectrum characteristic of collisional ionization equilibrium. Otherwise, in the winds of single O-stars, no electrons reach high temperatures and we observe instead the effects of the resonance between the macroscopic terminal velocity of the wind and the microscopic Bohr velocity characteristic of the electrons in bound atomic states.

## REFERENCES

Draine, B.T. & McKee, C.F. 1993, ARA&A, 31, 373

Ignace, R. & Gayley, K.G. 2002, ApJ, 568, 954

Miller, N.A. et al. 2002, ApJ, 577, 951

Pollock, A.M.T., et al. 2005, ApJ, 629, 482

Spitzer, L. Jr. 1962, Physics of Fully Ionized Gases, New York: Wiley, 2nd ed.

Waldron, W.L., & Cassinelli, J.P. 2001, ApJ, 548, L45

Zel’dovich, Ya.B. & Raizer, Yu.P. 2002, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena (Mineola, New York: Dover)