A new paradigm for the X-rays from O stars *

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Abstract: *XMM-Newton* observations of ζ Orionis suggest a new framework for the 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 electron heating does not take place, reducing the continuum. The spectrum is excited instead by protons with the randomized ion velocity dispersion accounting for the line widths. X-ray spectra in both single and binary stars are likely to be determined by the amount of post-shock electron heating: magnetically-confined plasma can evolve to high electron temperatures while in single stars this does not take place. The long mean-free path for Coulomb energy exchange suggests a minimum scale length for any structures in stellar winds, throwing into doubt the large-scale development of instability-driven shocks.

1 Shape of the X-ray lines in ζ Orionis.

The O9.7 Ib supergiant ζ Orionis is the optically brightest O star and was observed early 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 (Jansen et al 2001) 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 beyond 25Å to the N VI lines near 29Å and C VI near 34Å. The RGS is able to resolve 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 and shows that the broad lines continue to longer wavelengths. Where they overlap, the RGS and HETG spectra are essentially identical. In common with other O stars, the continuum is weak or absent.

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*Based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA

▪ "Massive Stars and High Energy Emission in OB Associations"; Proc. JENAM 2005 *Distant Worlds*, Liège (Belgium), eds. Rauw et al., p. 35-38 ▪

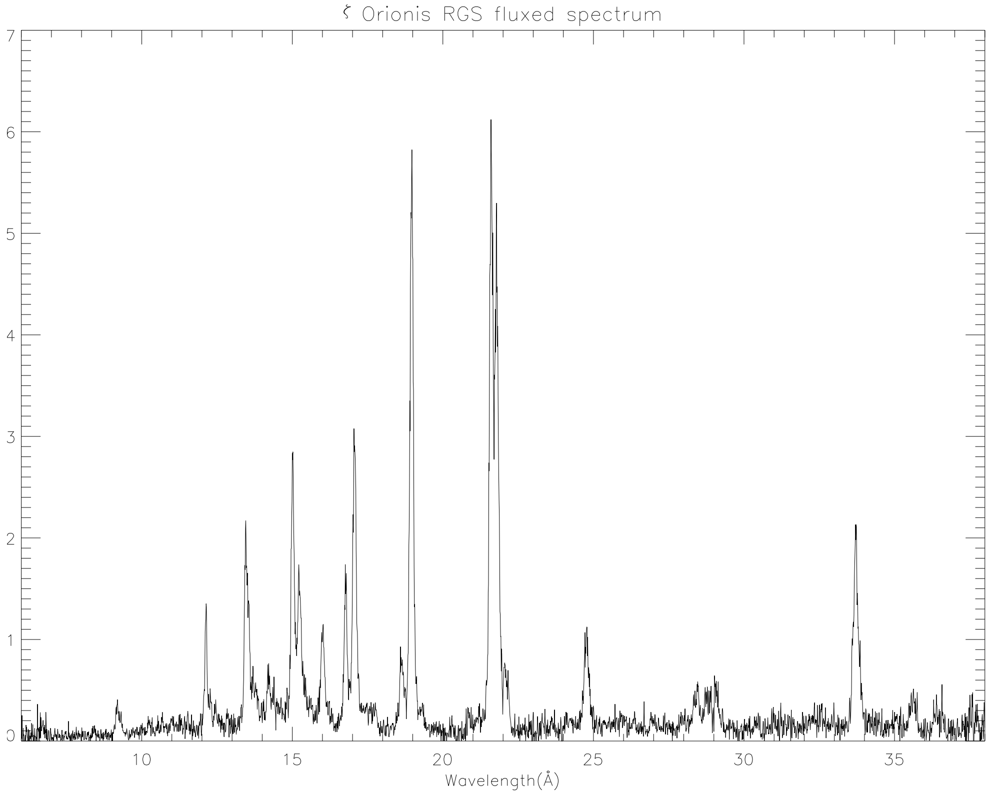

Figure 1: The RGS spectrum of ζ Orionis on 2002-09-15.

Comparison, for example, of the Lyα lines of C VI $\lambda33.734$ and Ne X $\lambda12.132$ separated by nearly a factor of 3 in wavelength shows their shapes in velocity space were very similar. In fact, 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 ζ Orionis's lines with the line centre blue-shifted by about -300km s^{-1}. The blue and red widths are similar although the solution with blueV=redV is excluded. Both are about 70 to 80% of ζ Orionis's terminal velocity of $v_\infty = 2100$km s^{-1}.

blueV	-1585 ± 25	km s^{-1}
centralV	-303 ± 31	km s^{-1}
redV	$+1723\pm30$	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 ζ Orionis.

2 The nature of shocks in O-star winds

The general physical principles governing the development of shocks (Zel'dovich & Rayzer 2002) were considered recently by Pollock et al. (2005) for the binary-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 that couple, for example, the small minority of UV-driven ions to the rest of the flow. In more extreme conditions, plasma shock waves show properties that result from the particularly slow character of the energy exchange between ions and electrons. The ion-ion collisional mean-free path is $l_{\rm i-i} \sim 7.0\times10^{18}{v_8}^4/n_{\rm i}$ cm (Spitzer 1962) where $n_{\rm i}$ is the ion density and $v = v_8 \times 1000$km s^{-1}. Close to the photosphere of ζ Orionis, where the density is high and the velocity low, $l_{\rm i-i}$ is small, but then increases rapidly with radius. At about $3R_*$ above the stellar surface in the heart of the acceleration zone, $l_{\rm i-i} \approx 0.1R_*$ while at $10R_*$, $l_{\rm i-i} \approx R_*$. 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, because of the large difference between their masses, this happens about a factor of 50 more slowly than ion-ion collisions, with corresponding mean-free-paths 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.

2.1 X-ray ionization and excitation

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 roughly equal to the randomized pre-shock gas velocity, which has a well defined value of $v_\infty = 2100$ km s^{-1} in the terminal velocity regime of ζ 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 $v_{\rm Bohr} = 2188$ km s^{-1}. We suggest that it is the coincidence of this microscopic atomic value and the macroscopic terminal velocities of ζ Orionis and other O stars, that is the basic physical reason for the production of X-rays in hot stars. The X-ray spectrum should reflect the individual cross-sections of the three important processes of ionization, excitation and charge exchange between ions.

2.2 The velocity profile of the X-ray lines

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. This simple assumption is hard to justify, if only because much of the ordered motion of the wind needs to be converted to heat for X-rays to be observed at all. 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 ζ Orionis are roughly consistent with this scheme, showing half-widths of about 75% of the value of $0.51v_\infty$. The small observed blue-shift of about $v_\infty/7$ is probably connected with the strong-shock post-shock bulk velocity of $v_\infty/4$.

3 Other consequences

The long Coulomb collisional mean-free-path, apart from requiring a collisionless shock transition, probably also limits the steepness of pressure gradients that can be sustained by the medium and defines a minimum size for any structures in the hot gas. In this case, it is unlikely that the microscopic instability in the line-driving mechanism will be able to steepen into the macroscopic shocks widely thought to generate O-star X-rays: the instability would soon be limited by the difficulty of transferring momentum quickly enough from the unstable driven ions to the rest of the flow, causing breakdown of the single-fluid approximation as discussed, for example, for thin hot-star winds by Springmann & Pauldrach (1992).

An inevitable consequence of the scheme proposed is the effective absence of hot electrons in an O-star wind, altering the physical basis of the plasma emission models concerned. 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.

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