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Letter to the Editor

Hα polarization of wind-heated optical bullets in SS 433

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Abstract. Mechanisms for energy supply to the optical bullets are discussed. It is pointed out that in the case of heating by bullet collisions with the system wind, recently shown to be a likely heating candidate, impact polarisation of the H_α line should be generated. An estimate shows that this line polarisation should be at least 0.2% and orthogonal to the jet, precessing with it on the sky. This should be observable and is proposed as a diagnostic of the wind heating model, in contrast to turbulent internal heating.

Keywords: stars - emission line, Lines - formation, polarisation.

Introduction Ever since the discovery of the strange emission line star SS433, it has been widely recognised that production of the optical luminosity of the 'bullets' comprising its jets demands that their thermal energy be continuously replenished - otherwise the system's kinetic luminosity would be absurdly large. It remains unclear, however, whether this bullet heating arises by dissipation of turbulent motions internal to the bullet, by extraction of bullet kinetic energy through interaction with the stellar wind present, or by absorption of radiation from the source of the jets or its companion star. Brown et al. (1991) have recently argued that adequate turbulent heating would broaden spectrum lines more than is observed, and that radiative heating will be much less important than wind heating for the observed wind density, unless the radiation source is highly beamed along the jet axis. Davidson and McCray (1980) also pointed out that radiative heating would impose yet another demand on the (already hard-pressed) power resources of the central object, when an ample supply of power is already potentially available from the bullet motion itself. Since the wind heating hypothesis for optical bullets leads to bullet masses and other parameters broadly consistent with other data (Brown et al. 1991), this mechanism appears to be the most probable one. It is of interest, therefore, to consider any possible direct observational diagnostic of the presence of such wind heating.

1.Heating Diagnostics Bullet heating by interaction with the stellar wind has been described in various ways. In the fluid scheme, the heating is envisaged in terms of absorption of x-rays generated in a shock layer between bullet and wind (Begelman et al. 1980). However, the Coulomb mean-free-path of a 34 MeV wind proton seen in the bullet frame is $>10^{13}$ cm, for estimated optical bullet densities of $< 10^9$ cm^{-3}, which is comparable with the bullet radius at optical emission distances. Unless a magnetic field plays a controlling role in the bullet/wind interface interaction, it is therefore more appropriate to discuss the interaction in kinetic rather than fluid terms - i.e. in terms of the collisional degradation of high energy wind particles in the bullet (cf. Davidson and McCray 1980 , Brown et al. 1991).A number of direct diagnostics for such particle collision processes are known in the context of particle beams in laboratory and solar flare plasmas. For example,high energy protons turn into high energy neutrals by charge exchange and subsequently emit 'non-thermal' Lyman-alpha photons. (e.g. Orrall and Zirker 1976, Canfield and Chang, 1985). These are shifted in wavelength according to the proton velocity - in the case of SS433, the wind velocity - but in the heavily extinguished UV spectrum of SS433 would probably be unobservable. Secondly, nuclear collisions will result in gamma-ray line emissions but these are smeared by recoil Doppler broadening and would be very weak from SS433 (cf. Lamb et al. 1983, Ramaty et al. 1985, Brown et al. 1987). Thirdly, impact of the wind protons on bullet neutral hydrogen atoms will result in linearly polarised impact excitation lines such as H_α, as in the solar flare situation (e.g. Henoux et al. 1990). The cross-section for this last process is sufficiently large that significant polarised photon fluxes may be anticipated and the diagnostic has the attractive property of carrying information on the incident proton direction. In this Letter we estimate what magnitude and direction of such impact polarisation in the H_α line should be expected from the wind heated model of SS433 bullets, as a prospective test of the wind heated model and its description in kinetic terms. Before doing so we note that heating of the bullets by radiation from a remote source can also produce linearly polarised lines through fluorescence as in nebular emission line polarisation, but for the same reasons as given by Brown et al. (1991) in relation to radiative heating, we do not expect this process to be significant compared to collisions. No such effect should be present in bullets heated by internal turbulent dissipation. While probably present in shock heated magnetised bullet models, the effect will be much smaller than in the case of direct heating by particle collisions because of the small volume of collisional interaction and the randomisation of wind proton directions in the shock region. The detection of H_α impact polarisation in SS433 would thus be an important diagnostic of bullet heating processes. Though SS433 has been observed polarimetrically, the observations have either been very broad band (McLean and Tapia 1980), or in a band around H_α (Efimov et al. 1984) too broad to isolate impact line effects from continuum Thompson scattering, or in circular polarisation only (Liebert et al. 1979)

2.Polarisation Estimate. Since the massive bullets will present 'collisionally thick' targets to the wind protons (cf. Brown et al. 1991), the total rate for any collisional process can be readily calculated regardless of the detailed spatial distribution of the bullet matter by the same method as given by Brown (1971), for solar hard x-ray emission by electron beams though noting that protons, unlike electrons, undergo negligible deflection as they stop.We consider the wind protons in the bullet frame as a beam of total power H_w, each proton having individual energy E_o. Each wind proton will excite through impact collisions, an H_α luminosity (ergs s^{-1}) of

$$L_{wp}(E_o) \;=\; \varepsilon_\alpha \int_{E_o}^{E_1} \sigma_\alpha(E)\,dN \;=\; \varepsilon_\alpha \int_{E_o}^{E_1} \frac{\sigma_\alpha(E)\,dE}{E\,\sigma_c(E)} \qquad (1)$$

where σ_α is the cross section for collisional excitation of H_α, ε_α is the energy of each H_α photon, E_1 is the threshold energy for the collisional excitation process, N is the column depth traversed by the proton, and σ_c is the collisional energy loss cross section . Although σ_α declines at high energies, it does so less quickly than σ_c so that the largest contribution to the integral in (1) is at high energies.

The total impact excited H_α luminosity emitted by the bullet due to incident wind protons will thus be

$$L_{p\alpha} \;=\; L_{wp}(E_o)\,H_w\,/\,E_o \quad \text{ergs } s^{-1}$$

To find the total polarisation emitted we must insert in (1) the polarization fraction ,p_α and define $\eta(E_o)$

$$\eta(E_o) \;=\; \varepsilon_\alpha \int_{E_o}^{E_1} \frac{\sigma_\alpha\, p_\alpha(E)\,dE}{E\,\sigma_c(E)} \qquad (2)$$

in which case the total polarisation, P_α is given by

$$P_\alpha \;=\eta(E_o)H_w/E_oL_\alpha$$

where L_α is the total H_α luminosity of the bullet . If we relate L_α to the wind heating power H_w by $H_w = f\,L_\alpha$ then our final expression for net polarisation is

$$P_\alpha = f\,\eta(Eo)\,/\,E_o \qquad (3)$$

The value of f will be 1 if H_w is the only source of bullet heating and is just balanced by L_α as the only source of bullet cooling. If H_w is the only source of bullet heating then f will in fact be >> 1 since there are other radiative losses than L_α . On the other hand, bullet heating and L_α generation by processes other than H_w would tend to decrease f. The arguments presented by Brown et al.(1991) suggest that the latter case is unlikely, but we will be conservative and estimate P_α for the case f=1. This is then a lower bound estimate.

We have calculated P_α from (2) and (3) using the energy loss cross-section σ_c according to Emslie (1978) and the experimental impact cross section σ_α and polarisation p_α given in Henoux et al. (1990) and references therein. The latter are not given at energies above about 200 keV and we have therefore used the analytic extrapolation of McFarlane (1974), according to the Bethe approximation, up to 34 MeV. Again to be conservative we have used the smallest reasonable extrapolated values to give a lower bound estimate for P_α.

Excitations from level 2 of hydrogen have, in the appropriate temperature regime, been included. The population of level 2 is determined by a Boltzmann distribution of occupancies in a bullet in L.T.E., and in the case where collisional ionisation from the ground state is important, and the equilibrium of level 2 is between radiative recombination and Lyman alpha emission. This second case is reasonable if we are in a regime where the ionisation balance within the bullet is determined collisionally rather than by a radiation field. Our expressions for this come from Krolik and McKee (1978). In both cases we have imposed the condition of optical thickness to Lyman lines.

Since we are here making the limiting assumption that all energy delivered to the bullets by wind protons is converted to thermal or collisional H_α, the temperature and density of the bullet are irrelevent, apart from how they dictate the relative occupation numbers, $n_1$and n_2 of the ground and second levels of Hydrogen,. (The cross sections for excitation from level 2 is higher than that from level 1 so we would expect the impact excited H_α luminosity, $L_{p\alpha}$ also to be higher, resulting in a higher P_α.) The diluting thermal component is at its absolute maximum assuming wind heating to be the source of heating . An explicit calculation of thermal $H_\alpha$emissivity as a function of bullet temperature and density, need not, in this limiting case, be done.

The bullet density enters in the calculation of level occupations also. We find that, using expressions in Krolik and McKee, and in Osterbrock, applicable to homogeneous spherical bullets in the collision dominated regime, that the ratio n_2/n_1 is proportional to $n_e\tau$ and use the argument in Davidson and McCray that efficient trapping of Lyman alpha photons occurs for $n_e\tau > 10^{16}$. Here we again set a lower limit to n_2/n_1, and hence to the polarisation fraction by using the value 10^{16}.

We find that for bullet temperatures in the region 0 to 13000K, $P_\alpha \sim 0.2\%$, which should be observable, for a jet seen approximately side on, as is the case for SS433. It will undergo a slight modulation in magnitude as the jets precess, and have a direction orthogonal to the jet, swinging on the sky through twice the jet precession cone angle, viz 40°. At temperatures outside this range P_α drops rapidly as the occupancy of levels 1 and 2 decrease (higher n states are increasingly filled).

We anticipate, however, that the thermal emission of the bullets at other frequencies, both in line and continuum, will lead to a higher value of P_α by reducing the fraction of H_w going into thermal H_α. The contribution of thermal Lyman alpha alone, should we allow the optical depth to decrease and assume the UV spectral extinction to be interstellar, could increase P_α by a factor of 10. Certainly, other redshifted lines are observed, indicating that some fraction of H_w goes to produce lines other than the diluting thermal H_α.

3.Conclusions We predict a minimum impact polarisation of 0.2% resulting from wind heating of the bullets, with direction on the sky orthogonal to the jets, rocking through about +-20° as the jets precess. We expect this impact polarisation to be produced only in the red and blue shifted jet components of the H_α. profile from the source, not in the stationary line (assuming that there is negligible neutral hydrogen in the wind.) If polarisation appears in the stationary line this is likely to be due to the effects of the interstellar medium and can be removed by use of the anticipated time variability of the moving line polarisation (cf. Brown et al. 1978. We hope that attempts will shortly be made to observe this polarisation, giving further evidence to help support or refute the wind heating model.

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