A new paradigm for X-ray emission from the winds of hot stars -or- all you ever wanted to know about proton(not photon or electron)-ionized plasmas

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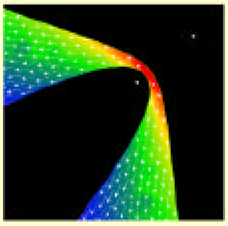
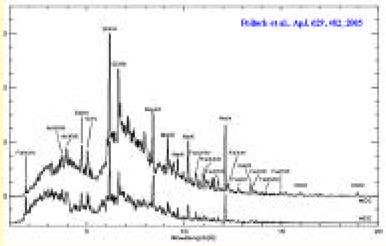
The Colliding Winds in WR140

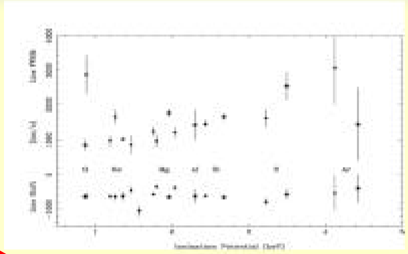


WC7+O4-5
$a \sin i = 14.1 \pm 0.5$ AU
$e = 0.881 \pm 0.005$
$1-e \leq (D/a) \leq 1+e$
WC $v_\infty = 2860$ km/s
O $v_\infty = 3200$ km/s

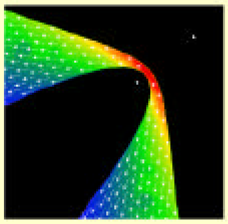
Chandra HETG X-ray spectra of WR140



X-rays from binary hot stars: WR140's lines



X-rays from binary hot stars: WR140's shocks



$a \sin i = 14.1 \pm 0.5$ AU
$e = 0.881 \pm 0.005$
$1-e \leq (D/a) \leq 1+e$

Coulomb collisions

collisionless shocks

$l_{ion-ion} \approx 14 (D/a)^2$ AU
$l_{ion-electron} \approx 21 (D/a)^2$ AU
$l_{electron-ion} \approx 8 (D/a)^2$ AU

WR140 (WC7+O4-5) – the prototype colliding-wind binary

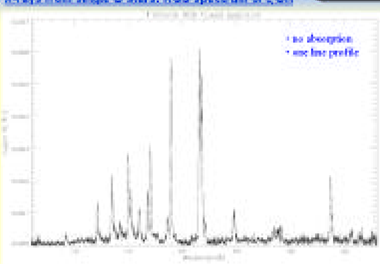
What and where are collisionless shocks ?

- boundary conditions demand that supersonic plasma is stopped
- gas-kinetic collisions are non-existent and Coulomb collisions too slow
- B and plasma processes take over
- all pre-shock particles have the same directed incoming v_∞
- all post-shock particles have the same randomised v_∞ and thus different T
- ions are heated at the shock front
- electrons are not heated much at the shock front
- Q : Where are they ? A : Everywhere in low-density plasmas !
- e.g. Interaction of the solar wind with the Earth's magnetosphere
- e.g. SNR blast waves

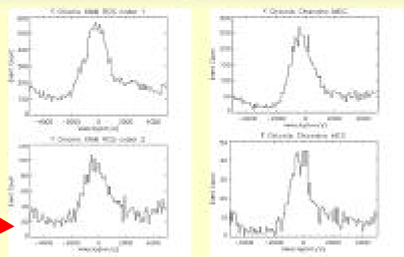
Key deductions for X-rays from WR140

- post-shock energy exchange between ions and electrons is slow
- line widths increase with ionization potential as electrons heat up
- plasma is not in equilibrium
- no sign of ionization precursor ⇒ electron conduction inhibited by B
- non-thermal particle acceleration (aka Cosmic Rays)

X-rays from single O stars: RGS spectrum of ζ Ori



The X-ray line profile of ζ Ori $v_\infty = 2100$ km/s



Conditions in a post-shock ideal gas

$v_{out} = (1/4) v$

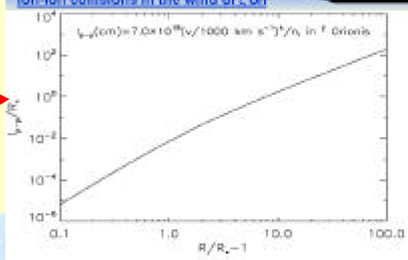
$(kT/m) = (3/16)\, v^2$

$T_X \approx 2 \mu v_8^2$ keV

$l_{ii} \approx 7.0 \times 10^{18}\, v_8^4 / n_i$ cm

$l_{ei} \approx (m_e/m_i)^{1/2}\, l_{ii}$

Ion-ion collisions in the wind of ζ Ori



z Ori (O9.7Ia) – the prototype single O-star wind

Key facts and deductions from the RGS spectrum of ζ Ori

- no obvious absorption (c.f. Vela X-1) even at long wavelengths
- lines resolved and have the same shape from Si XIII to C VI
- energy exchange is slow on both sides of the shock

⇒

- single-star shocks are also collisionless (and thus B rules)
- electrons keep cool and do no ionization or excitation and make no continuum
- post-shock plasma is not photoionized either but protoionized ($v_\infty \approx v_{Bohr}$) !
- shock thermalization of v_∞ gives $v_t = (kT/m)^{1/2} = (\sqrt{3}/4) v_\infty$: HWHM ≈ 0.51 v_∞
- shock-processed ions and electrons are soon quenched by the majority cool gas
- plasma is not in equilibrium
- X-ray spectra are distinguished by T_i (single stars low T_i | binaries high T_i)

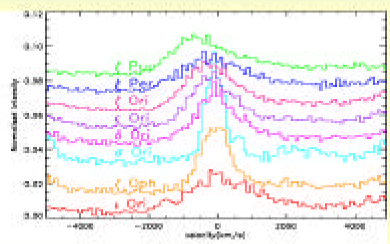
Ion-ion interactions in stellar winds

- $v_\infty = 2100$ km/s
- $v_{Bohr} = 2188$ km/s
- $\sigma_{ii} \approx 10^{-17} - 10^{-14}$ cm²
- $\sigma_{Coulomb} \approx 10^{-20}$ cm²
- $\sigma_{photoelectric} \approx 10^{-21}$ cm²
- σ_{ii} = excitation ⊕ ionization ⊕ charge exchange
- He-like f/r ratios could result from charge exchange (c.f. comets) not FUV

Further implications of slow Coulomb exchange

- Unless the magnetic field takes over…
- The mean-free-path l_{ii} defines the minimum dimension of wind structures
- Hot and cold material mix
- There is no contact discontinuity in colliding-wind binaries
- Line-driven instabilities do not develop into shocks

Chandra MEG combined profiles of other OB stars



	redV	centralV	blueV
ζ Pup	-2068	-829	+1937
ξ Per	-2180	-408	+2488
ζ Ori	-1585	-303	+1723
ε Ori	-1495	-251	+1480
δ Ori	-1615	-76	+1675
σ Ori	-552	-94	+617
ζ Oph	-1055	-27	+707
ι Ori	-2113	-44	+2262

velocities (km/s)

- a single triangular profile works well for all the lines in these OB stars

The new X-ray paradigm for single O stars

- There are no line-driven-instability shocks
- There are no hot electrons, no radiative shocks and no continuum
- There is no equilibrium
- The spectrum is excited by collisions between ions
- Charge exchange is important
- It happens in the terminal velocity regime
- The line width is thermal
- The line blue shift is from $v_\infty/4$
- It's collisionless
- It's magnetic
- It's partly non-thermal
- It's T_i

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