X-raying Hot Massive Stars

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Massive Stars and Stellar Winds

- Initial mass $M_\star > 15M_\odot$
- Main Sequence: OB-type
- Fast evolution (~Myr) → trace star formation
- Hot. $T_{\text{eff}} > 10,000$ K → high surface brightness
- Photon momentum → acceleration of matter
- Radiative acceleration larger than gravitation → supersonic STELLAR WIND

nasaimages.org
The evolution of (very) massive stars

Evolution ← stellar wind (!)
- O and B type stars
- Luminous Blue Variables
- Wolf-Rayet (WR) stars

According to dominant spectral lines
- WN (nitrogen) → WC (carbon) → WO (oxygen) → SN

supernova remnant G292.0+1.8
Massive stars: the cosmic engines

- Massive stars generate most of the ultraviolet radiation of galaxies: re-ionization of the Universe was largely due to first (super)massive stars
- Massive stars heat the dust and power infrared luminosities of galaxies

Massive stars: the cosmic engines

- Massive stars & their SNe input metals and energy in the ISM

HST: 30 Dor in the LMC
Massive stars: the cosmic engines

- Massive stars regulate evolution of star clusters

HST: Quintuplet cluster
Massive stars: the cosmic engines

- Massive stars are progenitors of black holes and neutron stars born in core-collapse SNe and/or $\gamma$-ray bursts

Artist impression of $\gamma$-ray burst
Massive stars are unique physical laboratories

- Nucleosynthesis
- Stellar interiors and evolution
- Interaction between radiation and matter
- Magnetic fields
- Stellar wind hydrodynamics
- Radiative transfer

**Warum ist es schwierig, WR-Atmosphären zu modellieren?**

Weil Plasma *nicht* im thermodynamischen Gleichgewicht
LTE (*Local Thermodynamical Equilibrium*) → Non-LTE

**Strahlungstransport (DGL)**
Symbolisch: lineare Abb. \( \Lambda \)

**Statistisches Gleichgewicht**
Lineares Gleichungssystem, lokal

\[
J = \Lambda S(n)
\]

\[
\vec{n} \cdot \mathbf{P}(J) = [0, \ldots, 0, 1]
\]

- Strahlungsfeld
- Quellfunktion
- Besetzungs- oder Übergangs- oder räumliche Kopplung
- Besзванenzahlen oder Übergangsraten

\[
R_{lu} = \int \frac{4\pi}{hv} \sigma_{lu}(\nu) J_{\nu} \, d\nu
\]

- Kopplung der Frequenzen
- Hochdimensional, nicht-linear, voll gekoppelt in Ort und Frequenz
X-ray astronomy is at the frontiers of observational astrophysics

Eight active missions:

perhaps the most observed band of EM spectrum from space

Chandra 1999

XMM-Newton 2000

Suzaku 2005
Multiwavelength approach

- IR
- optical
- UV
- X-ray

Modern observational data - unprecedented quality.

New level of sophistication in modeling and theory is required to understand the data.
X-ray emission from massive stars: Science objectives

- Physics: how X-rays are produced in massive stars?
- X-ray spectroscopy is a sensitive probe of stellar winds
- X-ray emission is a sensitive probe of stellar feedback
1. How X-rays are produced in massive stars?
OB stars are X-ray active (Einstein observatory 1978)

Hot stars: radiatively driven stellar winds

Supersonic stellar winds are intrinsically unstable

Shocks can also result from:
- Collision of streams in magnetically confined wind
- Collision of winds in binaries

Lucy Solomon (1970) ... Feldmeier et al. (1997)
Best quality X-ray spectra before year 2001 (ROSAT)

ζ Puppis

ζ Orionis
High-Resolution X-ray Spectra (XMM-Newton)

- Overall spectral fitting → plasma model, abundances
- Line ratios → $T_X(r)$, spatial distribution
- Line profiles → velocity field, wind opacity
Analyses of the X-ray spectra of O-stars

Temperature
- Range from 2 MK to 10 MK

Emission line profiles
- Broad; width scales with wind speed
- Similar across the spectrum
  Clumped wind (Feldmeier et al. 2003)
  OR plasma is not in CIE (Pollock 2007)

Line ratios in He-like ions
- Formed close to the photosphere
- Temperature decreases outward

Abundances
- Agree with wind abundances

X-rays can be explained by wind shocks (..?)

~100 papers based only on XMM data: e.g. Kahn et al. 01,
  Leutenegger et al. 2007, Naze et al. 2010, Raassen et al. 2005,
  Sana et al. 2004, Rakowski et al. 2006 ...
Stationary plasma in B-stars

- Wind speed is 1500 km/s
- But lines are narrow: Comparable to instrumental profile!
- He-like ions: f/i line ratio probes distance to stellar photosphere

Flux (Counts/sec/Angstrom)

X-ray plasma in B-stars

- Close to the photosphere
- Stationary
- Different from shocks in O-type winds

Pulsations? Coronae?
Wolf-Rayet type stars

Image courtesy of D. Ducros and ESA
X-ray view on single Wolf-Rayet Stars

- Not all WR stars emit X-rays.
- X-ray spectra of X-ray emitting WR are harder than spectra of O-stars
- Single WR carbon stars are X-ray quiet
- X-ray bright WR stars are binaries

Glimpse at the pre core-collapse star WR142 (WO)

- Requires state-of-the art non-LTE models to fit observed optical and UV spectra. Such as PoWR code (Hamann et al. 2006)
- \( T_\ast =160 \) kK, \( R_\ast =0.5R_\odot \), wind speed \( v=6000 \) km/s
- Our analysis indicates that star may be a FAST ROTATOR \( V_\text{rot} \sin i =4000 \) km/s. Current mass \( \sim 10 \) M\( \odot \)
XMM-Newton discovery of X-ray emission from a WO-type star

- X-rays are too hard to be explained by wind shocks
- Hint on the presence of magnetic field $B(2R_*) > 7$ kG
ARE GAMMA-RAY BURSTS IN STAR-FORMING REGIONS

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ABSTRACT

The optical afterglow of the gamma-ray burst GRB 970508 ($z = 0.835$) was a few hundred times brighter than any supernova. Therefore, the name “hypernova” is proposed for the whole GRB/afterglow.

"A very energetic explosion of a massive star is likely to create a ... fireball.... the inner core of a massive, rapidly rotating star collapses into a $\sim 10\, M_\odot$ Kerr black hole ... A superstrong $\sim 10^{15}\, G$ magnetic field is needed to make the object ... a microquasar. Such events must be vary rare...to account for the ... GRBs"
Physics of X-ray emission from massive stars

‘Curiouser and curiouser!’ cried Alice
Carroll (1865)

- **B-stars**: not clear: magnetic fields, pulsation, winds.
- **O-stars**: more or less clear: winds.
- **WR-stars**: absolutely unclear (First spectrum : XMM large program 2010)
2. X-rays diagnostics of stellar wind
Image courtesy of D. Ducros and ESA
Microclumping vs Macroclumping.

- **Observations**: wind is inhomogeneous. **Theory**: density contrast in the wind

- **Microclumping**: strong assumption -- size is smaller than the photon free path.

- **Macroclumping**: New "break through" motivated by X-ray spectroscopy: clumps are realistic, i.e. allowed not to be optically thin.

- Standard situation **porosity**, e.g dust: Particles are **opaque**: radiation cannot go through.

- Our work: how does **macroclumping** affect spectral analysis.
Macroclumping: $\tau_{\text{clump}} \geq 1$
Microclumping: $\tau_{\text{clump}} \ll 1$
The impact of *clumping* on empirical mass-loss rates

"Macroclumping" diagnostic line opt. thick

*Porosity effect*:

\[ \kappa_{\text{eff}} < \kappa_{\text{smooth}} \]

Important consequence for mass-loss empirical estimates

Larger \( \dot{M} \)

Mass-loss: key parameter to stellar evolution models & stellar feedback
UV diagnostics: PV resonance doublet

- PV resonance doublet becomes much weaker if macroclumping is taken into account.
- This resolves the discrepancy between $\dot{M}$ from resonance line and $\rho^2$ diagnostics!
X-ray diagnostics: X-ray emission lines

Model emission lines

Wind opacity for X-ray drastically reduced by clumping

Opacity becomes "grey"

Similar line profiles across the spectrum
Observed and model lines of ζ Puppis (no fitting!)

Oskinova et al. (2006)
High-Mass X-ray Binaries as stellar wind probes

Compact object embedded in stellar wind of OBI star
separation $\sim 1R_*$
- Stellar wind accretion on neutron star
  high $L_X$, power-law spectrum

- X-rays photoionize small part of stellar wind: recombination
- X-rays suffer absorption in stellar wind

Vela X-1

Fast temporal variability in X-rays - High Mass X-ray Binaries

- X-ray light curve: strong variability
- Optical donor star O-type supergiant
- $L_X \approx 10^{35}$ erg/s - accreting black hole
Accretion in clumped wind

Figure 1. Schematic representation of our clumpy wind model. $d$ is the distance between the centre of the clump and the center. $R_a$ is the accretion radius.
Stellar winds and X-ray spectroscopy

- Stellar wind is clumped
- Clumps are optically thick at some $\lambda$
- Clumps are most likely pancakes!
- Stellar mass loss rate is quite high

- New radiative transfer technique!
3. X-rays diagnostics of massive star feedback
S308 wind blown bubble around WR6, OSS
top: XMM-Newton image (Chu et al. 2003)
Massive star forming region ON 2 and star cluster Berkeley 87

Image courtesy of L. M. Oskinova, R. A. Gruendl, Spitzer Space Telescope,
JPL, NASA
X-ray observations help to understand feedback
Spitzer, HST, CXO, LMC 30 Dor (Townsley+’06)

- Spatial correlation of YSO and diffuse X-ray emission
- Chemical gradients
- Evolution of kinetic energy input
- X-ray dating of low-mass stars (perhaps high-mass, too?)

Evolution of $L_X$ from cluster wind

Oskinova 2005
Cosmic archaeology

- NGC 602 a massive star cluster (HST image)
- Example of triggered secondary star formation with a large yield
- X-rays trace hot plasma: how it is connected with star formation?
- NGC 602 is at the edge of a SUPERGIANT SHELL. Largest structures in the interstellar medium
Supergiant shell in the SMC
Part of the supergiant shell in the X-rays
From massive stars to structuring galaxies

- Supergiant shells are formed by massive star feedback?
- They provide chimneys for hot gas to escape to intergalactic space
- X-ray trace this hot gas and stellar feedback
**X-ray emission from massive stars: Summary**

- **Physics: how X-rays are produced in massive stars?**
  - Non-stationary processes in stellar winds: shocks, magnetic fields...

- **X-ray spectroscopy is a sensitive probe of stellar winds**
  - Mass-loss from massive stars is prodigious $10^{-4}...-7 \ M_\odot / yr$
  - Poorly known: standard methods need to be improved
  - X-rays: Winds are not stationary and not homogeneous - clumping

- **X-ray emission is a sensitive probe of stellar feedback**
  - Massive stars strongly affect the ISM by radiative (UV photons) and mechanic (winds) energy input.
  - How kinetic energy feedback affects the ISM and star formation?