HOT STARS, THEIR WINDS AND FEEDBACK

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MASSIVE STARS

M_i > 8 M☉

Depending on their initial masses (and other parameters...)

- **O-type star**
  - **Red Supergiant (RSG)**
    - (10⁶ yr)
    - V_∞ = 1000 km s⁻¹
    - V_∞ = 10 - 100 km s⁻¹
    - M = 10⁻⁹ - 10⁻³ M☉ yr⁻¹
  - **Luminous Blue Variable (LBV)**
    - (10⁵ yr)
    - M = 10⁻⁹ - 10⁻³ M☉ yr⁻¹
  - **Wolf-Rayet (WR)**
    - (10⁴ yr)
    - V_∞ = 1500 km s⁻¹
Feedback

- UV flux
- Proper motions

- Strong stellar winds ($V_\infty > 1000$ km/s)
- Supernova (SN) explosions
Stellar Feedback

Dense Material vs. Current Fast WR wind

Adiabatically shocked wind (e.g., Dyson & Williams 1997):

\[ T = \frac{3}{16} \frac{\mu m_H v_\infty^2}{k_B} \]

\[ = 2.3 \times 10^7 \mu \left( \frac{v_\infty}{1000 \text{km s}^{-1}} \right)^2 \] [K]

i.e., for \( v_\infty = 1000 - 2000 \text{ km s}^{-1} \)

Produce diffuse and Hot Bubbles!
\[ T = 10^7 - 10^8 \] K
\[ n = 0.001 - 0.01 \text{ cm}^{-3} \]
ζ Oph (O9.2 IV)
The first Hot Bubble around a single O-type star ever detected in X-rays!

Mackey et al. (2015)

Toalá et al. (2016)
DEM L50 - Superbubble

Superbubble in the LMC
- Stellar winds
- Supernova (SN) explosions

Jaskot et al. (2011)
- Mixing with the ISM
- SN impacts dominant sources powering X-ray emission!
Superbubbles
Superbubbles

e.g., Townsley et al. (2011, 2014)
Kuhn et al. (2013)

Large projects:
- The Chandra Carina Complex
- The OMNIBUS X-ray catalog
- The massive Young star-forming Complex Study in IR and X-ray (MYStIX)

Targets:
30 Doc  NGC 3603
G29.96-0.02  NGC 6334
G333.6-0.2  NGC 6354
M 16  W3
M 17  W4
NGC 3576  W51A
Superbubbles

The violent impact of Massive Stars!

- Hot gas permeates the Galaxy
- Recent shocks
- charge exchange reactions with the cold, dense molecular material

Townsley et al. (2014)
SGS-SMC I

Supergiant Shell (SGS)

Oskinova et al. (2013)
X-RAYS FROM MASSIVE HOT STARS

Thanks to the *Chandra* analysis of high-resolution spectra of hot stars, we now know that:

- The X-ray-emitting plasma around hot stars is very close to the photosphere
- It has a thermal origin
- X-ray lines are broad (well resolved by *Chandra*)
- Multi-temperature plasmas (up to 10 MK)
- X-ray variability

+ state-of-the-art nonLTE stellar atmosphere codes, such as PoWR & CMFGEN (e.g., Shenar et al. 2015; Puebla et al. 2016)

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*Chandra* analysis of high-resolution spectra of hot stars.
X-RAYS FROM MASSIVE HOT STARS

Single stars:
1) Shock heating due to line-driven wind instabilities

\[ \frac{L_X}{L_{bol}} \sim 10^{-7} \]

e.g. Feldmeier et al. (1997)
X-RAYS FROM MASSIVE HOT STARS

Single stars:
2) Magnetically Confined Wind Shocks

e.g., ud-Doula et al. (2014)
X-RAYS FROM MASSIVE HOT STARS

Single stars:
2) Magnetically Confined Wind Shocks

**X-ray Analytic Dynamical Magnetosphere (XADM) scaling law**

e.g., ud-Doula & Nazé (2016)
Petit et al. (2013)
Nazé et al. (2014)
X-RAYS FROM MASSIVE HOT STARS

Binaries
3) Colliding Wind Binaries (CWB)

Credit: NASA/C. Reed

e.g. Parking et al. (2011)
η Car (LBV - Binary)
The most luminous star in the Galaxy!

More than 1.47 Ms

Hamaguchi et al. (2014)
δ Ori (O9.5 II) - Large Program

480 ks
Chandra HETGS & ACIS-S

Corcoran et al. (2015)
Nichols et al. (2015)
Pablo et al. (2015)
Shenar et al. (2015)

- The X-ray emission is dominated by embedded wind shock emission from Aa I
- Variations of the emission line widths as a function of binary phase are found
- Modelling: turbulent velocities (200 km s\(^{-1}\)) and wind inhomogeneities
The Sgr A* X-ray Visionary Program

3 Ms *Chandra* Observations

Wang et al. (2013)

Cuadra et al. (2015)
Russell et al. (2015)

CWB feeding SgA* ..!
Wolf-Rayet (WR) stars

*Chandra* has devoted large time in studying WR stars: single and binaries! (See review by Oskinova 2016)

WR6

450 ks *Chandra/HETG*

The most detailed X-ray spectrum and analysis of a (single) WR star

- No Oxygen lines are detected
- X-rays-emitting is form out in the wind (He-like ions)
- X-rays between 10-100 R*

DIFFICULT TO RECONCILE TO THE LDW . . !
Planetary Nebulae

PNe are also hot!

Central Stars are also
Hot Stars with fast winds:
500 - 4000 km s$^{-1}$
(Guerrero & De Marco 2013)
Planetary Nebulae

PNe are also hot!

The *Chandra* Planetary Nebulae Survey (CHANPLANS)

$\sim 1.5$ Ms

All PNe close to the Sun ($d < 2$ kpc)

Kastner et al. (2012)
Freeman et al. (2014)
Montez et al. (2015)
BD+30°3639

Yu et al. (2009)
LEGT/ACIS-S

The highest-resolution spectrum of a Hot bubble

\( T_X = [1.7 - 2.9] \times 10^6 \) K
SUMMARY

- *Chandra* has played a major role in advancing our understanding of X-ray emission from Hot Stars and their Feedback.

- X-ray spectra from Hot Stars have helped constrain and test radiatively-driven stellar winds with the help of sophisticated non-LTE stellar atmospheres codes (e.g., PoWR & CMFGEN)

- TGCat archive of *Chandra* grating spectra - a great legacy to X-ray Astronomy (Huenemoerder et al. 2011) more than 400 objects!

- *Chandra* the perfect satellite to study star forming regions and compact objects (e.g., PNe)
Chandra & Hot Stars in the Next Decade (I/V)

- We need Chandra "sharp eyes" to unveil stellar feedback for low-metallicity media

- We need to invest large time (~Ms) studying stellar feedback in the SMC

- A large proposal will be submitted again next year
**Chandra & Hot Stars in the Next Decade (II/V)**

Diffuse X-ray emission around single O and WR stars

- ζ Oph
- NGC 6888 (WR136)
- WR 6
- WR 7
- WR 136
- WR 18

**XMM-Newton**

Toalá et al. (2012, 2015, 2016)
Chandra & Hot Stars in the Next Decade (III/V)

The weak-wind problem around late O and B-type stars - challenge the radiation-driven winds model (e.g., Puls et al. 2008; Najarro et al. 2011)

Ochsendorf et al. (2014)
Chandra & Hot Stars in the Next Decade (IV/V)

The future of the CHANPLANS project *Chandra* HRC and *XMM-Newton* EPIC for a better understanding of PNe (Improve plasma temperatures, abundances, electron densities, X-ray-emitting gas distribution…)

![NGC 1501](image)
Chandra & Hot Stars in the Next Decade (V/V)

WR stars

- WR6 is shaking our understanding of the X-ray emission from WR stars

- Deep, high-resolution X-ray spectra for different spectral types (WN, WC, WO) !!
THANK YOU
Chandra in the future . . .

Still some discoveries to make!

Searching for a monster lurking in a WR nebula
WR+NS??
Chandra observations accepted
(PI: Oskinova)