Stellar Winds and Hydrodynamic Atmospheres of Stars

Rolf Kudritzki
Spring Semester 2010
I. Introduction

First suspicion of existence of continuous stellar winds:

1929 C. Beals
MNRAS 90, 202
91, 966 (1931)

1934 S. Chandrasekhar
MNRAS 94, 522

Optical spectrum of P Cygni B2 hypergiant and LBV:
- broad H, HeI, metal lines with blue-shifted absorption red-shifted emission

Optical spectrum of Wolf-Rayet stars:
- broad He, C, N emission lines
- no hydrogen lines

widths of lines $\leftrightarrow$ Doppler-shifts of out-flowing atmospheres

$V_{\text{expansion}} \approx 200 \text{ km/s to } 3000 \text{ km/s}$
H and HeI lines of P Cygni

Note different y-scale of plots

Emission in H\(\alpha\) is huge

H\(\delta\) is much weaker

Najarro, Kudritzki et al. 1997
Same Fig. as before, but now \( \lambda - \lambda_0 \) replaced by \( v = \frac{\Delta \lambda}{\lambda} c \) estimate of outflow velocities
P Cygni - B2 hypergiant and LBV: Model atmosphere fit - optical lines

Najarro, Kudritzki et al. 1997
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  - broad H, HeI, metal lines with blue-shifted absorption
  - red-shifted emission

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Widths of lines ↔ Doppler-shifts of out-flowing atmospheres

\[ V_{\text{expansion}} \approx 200 \text{ km/s to 3000 km/s} \]
Wolf-Rayet star in NGC 300 at 2 Mpc distance


optical spectra of M supergiants
α Ori M2 Ib
α¹ Sco M1 Ib
α¹ Her M5 II
blue-shifted absorption cores of groundstate lines of MnI, CaI, CrI etc. ("0.00 eV lines")

modern spectra (high res. & S/N)
narrow P Cygni profile superimposed to photospheric line core

$v_{exp} \approx 10$ to $20$ km/s but $v_{esc} = [2GM/R]^{1/2}$ escape velocity is of same order!

Is the flow able to escape the gravitational potential ?????
α Ori


MnI

\( \lambda 4030.8 \ \text{Å} \)

\( \lambda 4033.1 \ \text{Å} \)

tiny P Cygni profile superimposed to photosperic line core
Mt. Palomar 5m Coude spectra with very high resolution of M supergiants with earlier spectral-type companions

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>α¹ Sco</td>
<td>M1 Ib</td>
</tr>
<tr>
<td>α² Sco</td>
<td>B2 V</td>
</tr>
<tr>
<td>α¹ Her</td>
<td>M5 II</td>
</tr>
<tr>
<td>α¹ Her</td>
<td>G0 III</td>
</tr>
</tbody>
</table>

- CaII, TII etc. lines very unusual for B2
- MNI, CrI etc. very unusual for G0

Circumstellar lines produced wind of M supergiant
wind envelope extension $\approx 1000 R_{\text{star}}$

$v_{\text{exp}} \approx 20 \text{ km/s} \gg v_{\text{esc}} = \left[\frac{2GM}{r}\right]^{1/2} \approx \frac{1}{30} v_{\text{esc-photosphere}}$

$V_{\text{exp}} \gg V_{\text{esc}} (r)$

$M$ supergiants have winds !!!
Solar wind

1951 Ludwig Biermann *Zeitschrift fuer Astrophysik* 29, 274
all comet plasma tails point away from sun
solar wind with $v \approx 400$ km/s

1962 Neugebauer & Snyder *Science*, 138, 1169
Mariner 2 probe to Venus finds
fast solar wind present all times

$v \approx 500 \pm 300$ km/s at Earth orbit
$n_{\text{wind}} = 5$ cm$^{-3}$ highly variable
$M = \text{some } 10^{-13}$ $M_{\odot}$/yr

first hydrodynamic theory of solar wind
II. Spectroscopic evidence for stellar winds

1. Spectral lines in hydrostatic atmospheres

Hydrostatic $\to$ barometric formula

$$\rho = \rho_0 \ e^{-\frac{r-r_0}{H}} \quad H = \frac{v_{\text{sound}}^2}{2g} \quad v_{\text{sound}}^2 = \frac{kT}{\mu_{\text{mol}} m_p}$$

$$\frac{H}{R} = \frac{1}{4} \frac{v_{\text{sound}}^2}{v_{\text{esc}}^2} \ll 1$$

thin, plane-parallel atmosphere with temperature gradient
symmetric absorption line around central wavelength $\lambda_0$

Width of line determined by

a) thermal motion of gas

$$v_{thermal} = \sqrt{\frac{2kT}{m_{atom}}}$$

b) stellar rotation

$$v_{rot} \cdot sini$$

c) Pressure broadening, stellar gravity

$$g_*$$
1. Line scattering in expanding atmospheres

in front of stellar disk: blue-shifted scattering by gas moving towards observer

remaining envelope: red- & blue-shifted scattering by gas moving towards and away from observer

P Cygni profile

width determined by $v_{\text{max}}$
Note: “line scattering” is special re-emission process

photon is absorbed and
re-emitted by spontaneous emission
in same line transition

de facto
scattering

number of photons is conserved

\[ N_{\text{abs}} = N_{\text{em}} \]

typical process for resonance lines
2. Thermal or recombination emission in expanding atmospheres

If \( \tau_{\text{spont}} > \tau_{\text{coll}} \)

- absorbed photon not re-emitted and destroyed by collisional level excitation or de-excitation
- re-emission coupled to local \( T(r) \)
- since wind envelope can a huge volume, an emission line might occur

pure emission profile

width determined by \( v_{\text{max}} \)
If ionization of the atoms with subsequent recombination dominates, then the population of the upper level is controlled from electron transitions cascading from above.

ionization from ground or excited level  

cascade of subsequent spontaneous emissions

pure emission line
3. Other signatures of stellar winds

Stellar winds are ubiquitous in all stellar domains !!!

**Radio:**
- **hot stars:** free-free emission of winds
  - “radio-excess”
- **cool stars:** maser emission of winds
  - OH, H$_2$O, SiO, NH$_3$

**IR:**
- ground-based & satellite telescope (IRAS, ISO, Spitzer, Herschel)
  - **hot stars:** free-free emission of winds
    - weaker than “radio-excess”
    - rich emission line spectra H, He, metals
  - **cool stars:** dust emission in winds, PAHs
P Cygni - B2 hypergiant and LBV: Model atmosphere fit – IR (ISO)

Najarro & Kudritzki, 1997
P Cygni

mid IR (ISO)

Najarro, 2005
Optical: line diagnostics of mass-loss rates
wind velocities
chemical composition
A-supergiant in M31 - stellar wind

\[ R_{ji} = 4\pi \left( \frac{n_i}{n_j} \right)^* \int \frac{\sigma_{ij}}{h\nu} \left( \frac{2h\nu^3}{c^2} + J_\nu \right) \exp\left(-\frac{h\nu}{kT}\right) d\nu \]


Keck, Hires
$H_{\alpha}$ emission B superrgiant - stellar wind

Model calculation


\[ R_{ji} = 4\pi \left( \frac{n_i}{n_j} \right) \int \frac{\sigma_{ij}}{h\nu} \left( \frac{2\pi c^2}{h^2} + J_\nu \right) \exp\left( -\frac{h\nu}{kT} \right) d\nu \]
$H_\alpha$ emission O-star

Model calculation

Variation of $\dot{M}$ by $\pm 20\%$

Kudritzki & Puls, 2000, AARA 38, 613
Wolf-Rayet star in NGC 300 at 2 Mpc distance

NGC 300 WN11 star

non-LTE line-blanketed hydrodynamic model atmospheres with stellar winds

stellar parameters
wind parameters
H, He, CNO, Al, Si, Fe abundances

**NGC 300 WN11 star**

<table>
<thead>
<tr>
<th>Species</th>
<th>Relative number fraction</th>
<th>Mass fraction</th>
<th>$X/X_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1.5E+00</td>
<td>2.7E-01</td>
<td>0.4</td>
</tr>
<tr>
<td>He</td>
<td>1.0E+00</td>
<td>7.2E-01</td>
<td>2.7</td>
</tr>
<tr>
<td>C</td>
<td>3.6E-04</td>
<td>7.7E-04</td>
<td>0.3</td>
</tr>
<tr>
<td>N</td>
<td>2.5E-03</td>
<td>6.3E-03</td>
<td>7.7</td>
</tr>
<tr>
<td>O</td>
<td>5.5E-04</td>
<td>1.6E-03</td>
<td>0.2</td>
</tr>
<tr>
<td>Al</td>
<td>5.0E-06</td>
<td>2.4E-05</td>
<td>0.4</td>
</tr>
<tr>
<td>Si</td>
<td>8.5E-05</td>
<td>1.7E-04</td>
<td>0.2</td>
</tr>
<tr>
<td>Fe</td>
<td>1.5E-04</td>
<td>1.5E-03</td>
<td>1.3</td>
</tr>
</tbody>
</table>
$T_{\text{eff}} = 10000\text{K}, \quad L = 3.1 \times 10^5 \, L_{\text{sun}}$

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Fraction $X/X_{\text{sun}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.688</td>
</tr>
<tr>
<td>He</td>
<td>0.301</td>
</tr>
<tr>
<td>Mg</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Fe</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

NGC 3621
7 Mpc

LBV

Najarro, Urbaneja, Kudritzki, Bresolin 2005
UV: satellite telescopes: Copernicus, IUE, HST, ORFEUS, EUVE, FUSE

very rich stellar wind spectra of hot and cool stars

OVI, OV, OIV, OIII, NV, NIV, NIII, CIV, CIII, CII, SiIV, SiIII, SVI, SV, MgII, FeII .....
UV spectrum of O4 supergiant z Puppis

Pauldrach, Puls, Kudritzki et al. 1994, SSRev, 66, 105
HD 93129A O3Ia

X-ray: hot stars: emit X-rays through shocks in their winds
strong X-ray emitters

cool stars: have coronae, except M supergiants/giants
time dependent stellar wind radiation-hydro → shocks
(Owocki et al., 1988; Feldmeier, 1997)
Calculated spectra and ROSAT observations
Feldmeier, Kudritzki et al., 1997

ζ Pup, O4 If  i Ori O9 III  15 Mon O7 V
III. Stellar winds and Astronomy

1. Stellar winds and galaxies

Massive stars dominate light of star forming galaxies

Strong and broad stellar wind lines easily detectable in spectra of integrated stellar populations

Example: starburst galaxies at high z UV shifted to optical/IR

population synthesis, metallicities, Energy and momentum input \(\rightarrow\) galactic winds, star formation
Nuclear burned material input \(\rightarrow\) chemical evolution of galaxies
P Cygni profiles and metallicity

Galaxy

LMC

SMC

Kudritzki, 1998
Population synthesis of high-z galaxies

Stellar spectra

Galaxy spectra

Stellar Population
Initial Mass Function
Star Formation History
Metallicity
Stellar Evolution

non-LTE atmospheres with winds plus stellar evolution models
→ Synthetic spectra of galaxies at high z
→ as a function of Z, IMF, SFR
Starburst99 population synthesis models + UV stellar libraries at ~solar and ~0.25 solar (LMC, SMC) abundance
Spectral diagnostics of high-z starbursts

Starburst models - fully synthetic spectra based on model atmospheres

Spectral diagnostics of high-z starbursts

Rix, Pettini, Leitherer, Bresolin, Kudritzki, Steidel

cB58 @ z=2.7

fully synthetic spectra vs. observation
2. Winds and stellar evolution

Winds affect stellar evolution significantly

\[ \dot{M} \] mass-loss

mass \( M \) is decisive parameter for stellar structure/evolution

\[ \dot{M} \] crucial in certain phases, because it changes stellar mass
stars with $M \leq 10 \, M_{\text{sun}}$

$\dot{M}$ significant during red giant stage

$\dot{M} \approx 10^{-4} \ldots 10^{-8} \, M_{\text{sun}} / \text{yr}$

$\t_{\text{evol}} \approx 10^8 \ldots 10^6 \, \text{yrs}$

good approximation

$\dot{M} = 5.5 \times 10^{-13} \frac{L/L_{\text{sun}}}{g/g_{\text{sun}} \, R/R_{\text{sun}}} \, M_{\text{sun}} / \text{yr}$


$v_{\infty} \approx 20 \ldots 40 \, \text{km/s} \quad T_{\text{wind}} \approx 300 \ldots 600K$

Note: tremendous mass-loss in RGS and AGB - phase
star with 8 $M_{\text{sun}}$ on main sequence ends up with 1 $M_{\text{sun}}$

7 $M_{\text{sun}}$ re-cycled to ISM
ejection of Planetary Nebula at tip of AGB
Late stages of low-mass stellar evolution: CSPN

\[ \dot{M} \approx 10^{-7} \ldots 10^{-9} M_{\text{sun}}/\text{yr} \]
\[ v_\infty \approx 500 \ldots 4000 \text{ km/s} \]
\[ t_{\text{tevol}} \approx 3 \times 10^4 \text{ yrs} \]

\[ M_{\text{lost}} \approx 3 \times 10^{-3} \ldots 3 \times 10^{-5} M_{\text{sun}} \]

small, but \( \approx \) mass of hydrogen burning shell

\( t_{\text{tevol}} \) strongly modified by winds

for review of CSPN winds see
Kudritzki, Mendez et al., 1997, Proc. IAU Symp. 180, 64
Kudritzki et al., 2006, Proc. IAU Symp. 234, 119
White Dwarfs: extremely narrow mass distribution

\[ \bar{M}_{WD} \approx 0.6 M_{\odot} \]

without mass-loss stars with such masses cannot have evolved from the main sequence within Hubble time

from the HRDs of open clusters we know the all stars with

\[ 0.8 \ M_{\odot} \leq M \leq 10 \ M_{\odot} \]

have formed WDs

The mass spectrum observed can be explained by IMF and stellar evolution with mass-loss applying Reimers - formula
stars with $M \geq 10 \, M_{\odot}$

Stellar winds observable during whole evolution

$$\dot{M} \approx 10^{-5} \ldots 10^{-9} \, M_{\odot}/yr$$

$$v_\infty \approx 200 \ldots 4000 \, km/s$$

$$\dot{M} \, v_\infty \propto L^{1.6}$$

Kudritzki & Puls, 2000, AARA 38, 683
Kudritzki & Urbaneja, 2009

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**strong $\dot{M}$ for $M \geq 40 \, M_{\odot}$**

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stars can lose up to 90% of their mass until He-ZAMS

**Wolf-Rayet stars:** massive stars on He-ZAMS with no H

$$\dot{M} \approx 10^{-4} \ldots 10^{-5} \, M_{\odot}/yr$$

$$v_\infty \approx 2000 \ldots 4000 \, km/s$$

very strong winds !!!
3. Winds and galaxy evolution

Stellar winds → Energy and momentum input into ISM

affects star formation
causes “galactic winds”
recycles nuclear burned matter into ISM
affects chemical evolution