WINDS OF HOT MASSIVE STARS

I Lecture: Hot massive stars and stellar winds

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Selected Topics in Astrophysics
Faculty of Mathematics and Physics
October 9, 2013
Prague

1. Overview of the course
2. Basic properties of hot massive stars
3. Importance of hot massive star research
4. Signature of stellar mass loss
5. How to release the matter from the surface of the star?
6. Basic wind types and their driving mechanisms

Overview of the course

First block

Hot massive stars and stellar winds

1. Basic properties of hot massive stars
2. Importance of hot massive star research
3. Signature of stellar mass loss
4. How to release the matter from the surface of the star?
5. Basic wind types and their driving mechanisms

Second block

Basic wind theory of hot massive stars

1. Properties of winds of hot massive stars
2. Line-driven wind theory
3. Wind hydrodynamics equations
4. The radiative force
5. Sobolev approximation

Overview of the course

Third block

Quantitative spectroscopy of winds of hot massive stars

1. Spectral diagnostics of stellar winds
2. P Cygni line profile formation
3. Photospheric parameters determination
4. Terminal velocity determination
5. Mass-loss rates determination

Fourth block

Wind inhomogeneities (clumping)

1. Small and large scale structure
2. Observational evidence
3. Theoretical predictions
4. Wind models with clumping
5. Open questions

Recommended literature

1. *Lamers, H. G. L. M.; Cassinelli, J. P.*: **Introduction to Stellar Winds** Cambridge University Press, 1999
2. *Fullerton, A. W.*: **Observations of Hot-Star Winds** Lecture Notes in Physics, Vol. 497, pp. 187-237, 1997
3. *Kudritzki, R.-P.; Puls, J.*: **Winds from Hot Stars** Annual Review of Astronomy and Astrophysics, Vol. 38, pp. 613-666, 2000
4. *Puls, J.; Vink, J. S.; Najarro, F.*: **Mass loss from hot massive stars** The Astronomy and Astrophysics Review, Vol. 16, Issue 3-4, pp. 209-325, 2008
5. *Krtička, J.; Kubát, J*: **Radiatively Driven Winds of OB Stars - from Micro to Macro** ASP Conference Series, Vol. 361, p. 153, 2007

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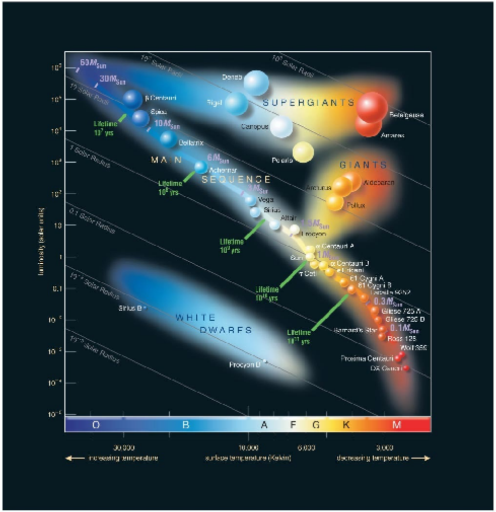
Basic properties of hot massive stars

- EXTREMELY LUMINOUS AND BRIGHT
  spectral types A, B, and O;
  $L \gtrsim 10^2$ [$L_\odot$]
  W-R, LBV, B[e] stars
- HOT - $T_{\text{eff}} \gtrsim 8\,000$ [K]
- MASSIVE - $M \gtrsim 2$ [$M_\odot$]

H-R diagram



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Typical parameters for O-type stars

Parameter	Sun	O-type stars
M [$M_\odot$]	1	$\gtrsim 8$
T_{eff}[K]	6000	$\gtrsim 30\,000$
L [$L_\odot$]	1	$\sim 10^6$
total life time [yr]	10^{10}	$\sim 10^7$
T_{wind}[K]	10^6	$\sim 10^4$
$\dot{M}$[$M_\odot$ yr^{-1}]	10^{-14}	$\sim 10^{-6}$
v_∞[km s^{-1}]	400 (700)	$\sim 10^2 - 10^3$

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- SMALL FRACTION OF THE STELLAR POPULATION

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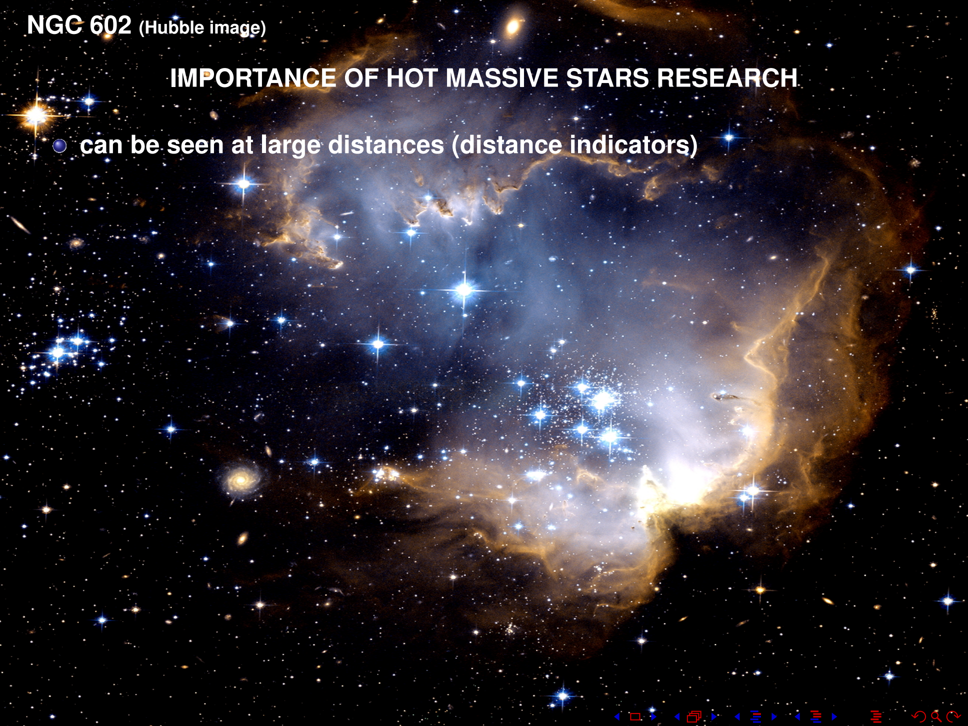
ALL OF THEM LOSE THEIR MASS

NGC 602 (Hubble image)

IMPORTANCE OF HOT MASSIVE STARS RESEARCH

- can be seen at large distances (distance indicators)



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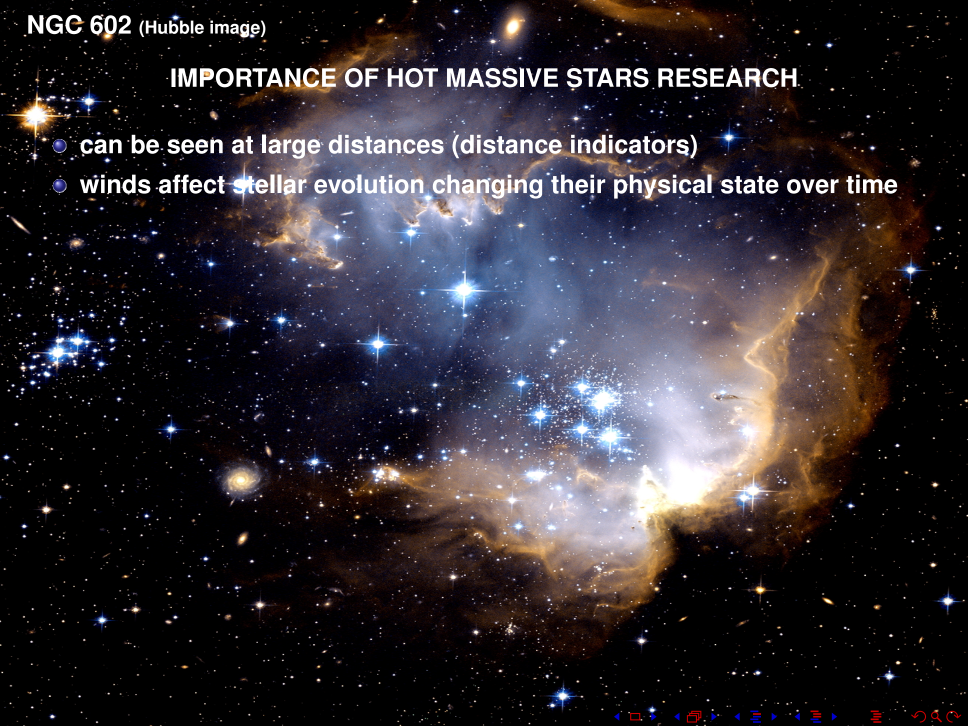

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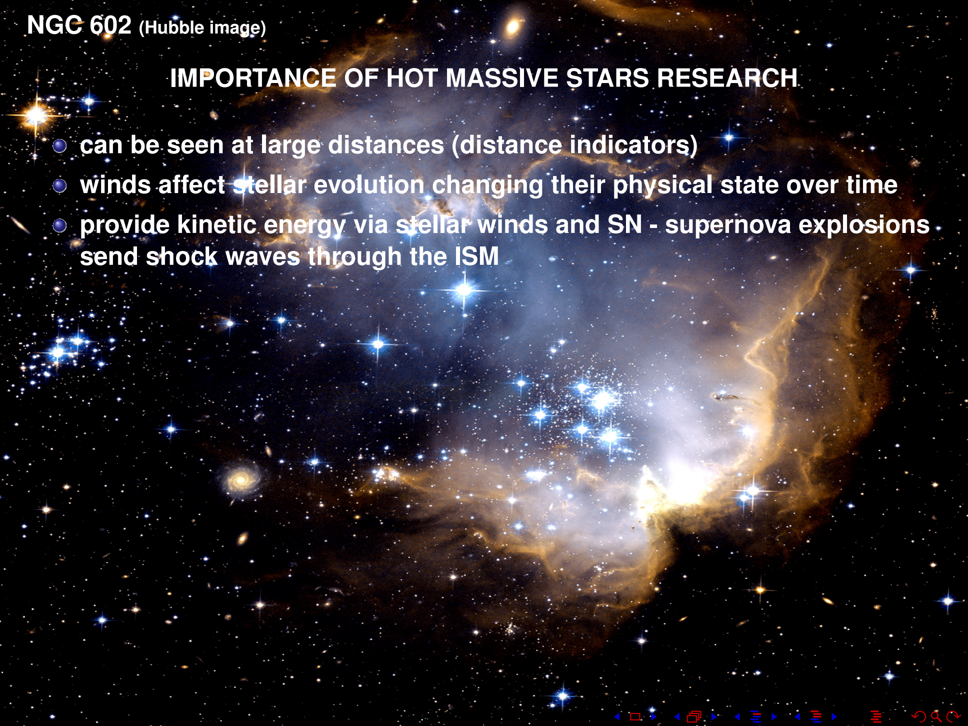
- provide kinetic energy via stellar winds and SN - supernova explosions send shock waves through the ISM



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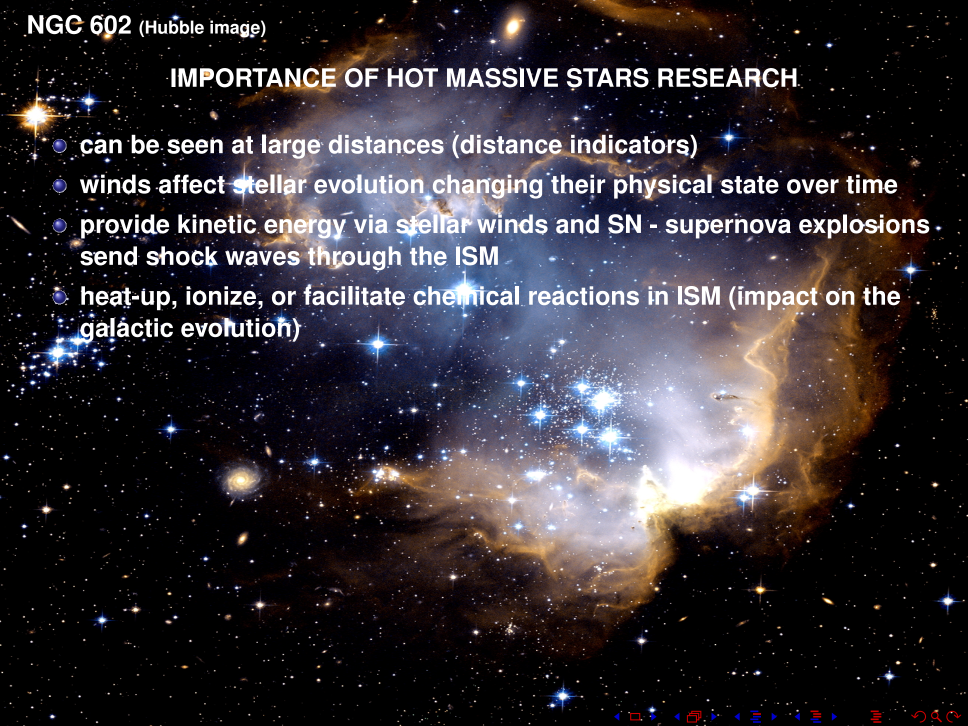

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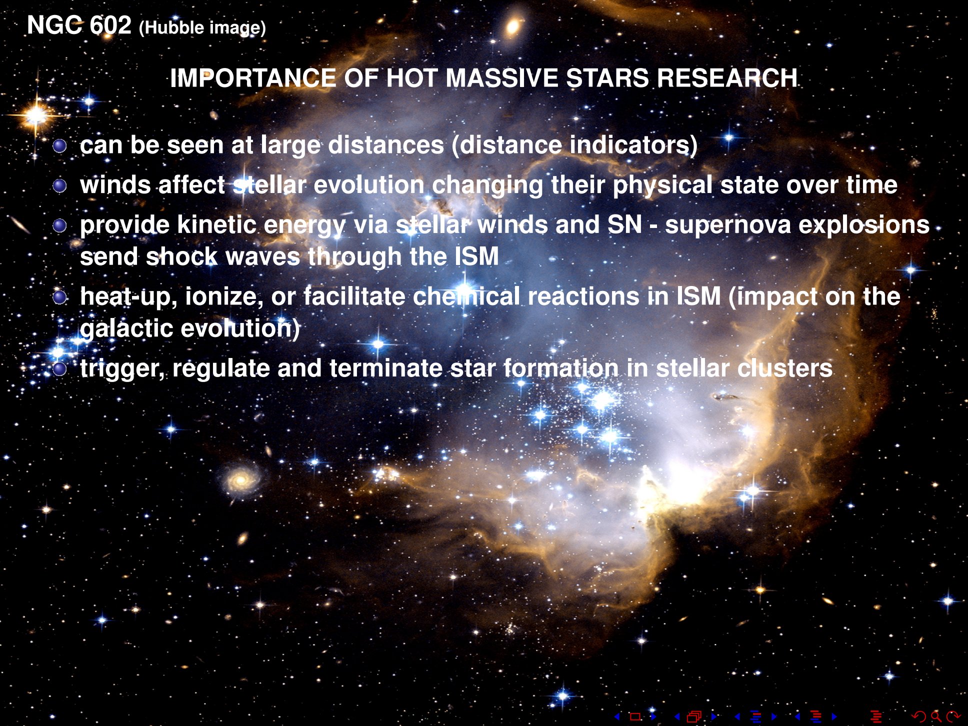

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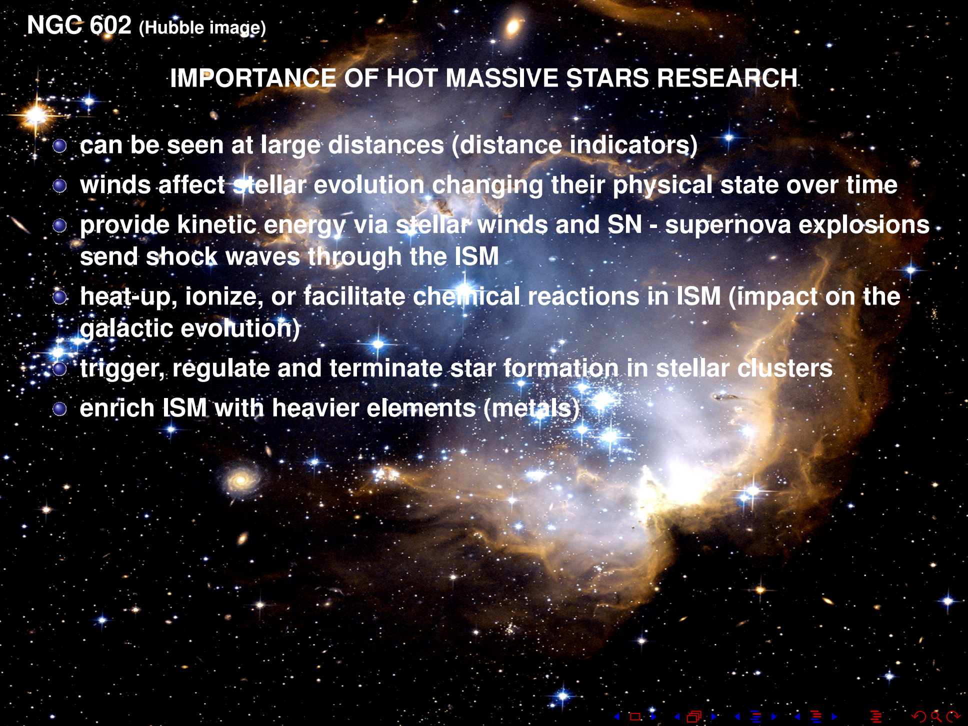

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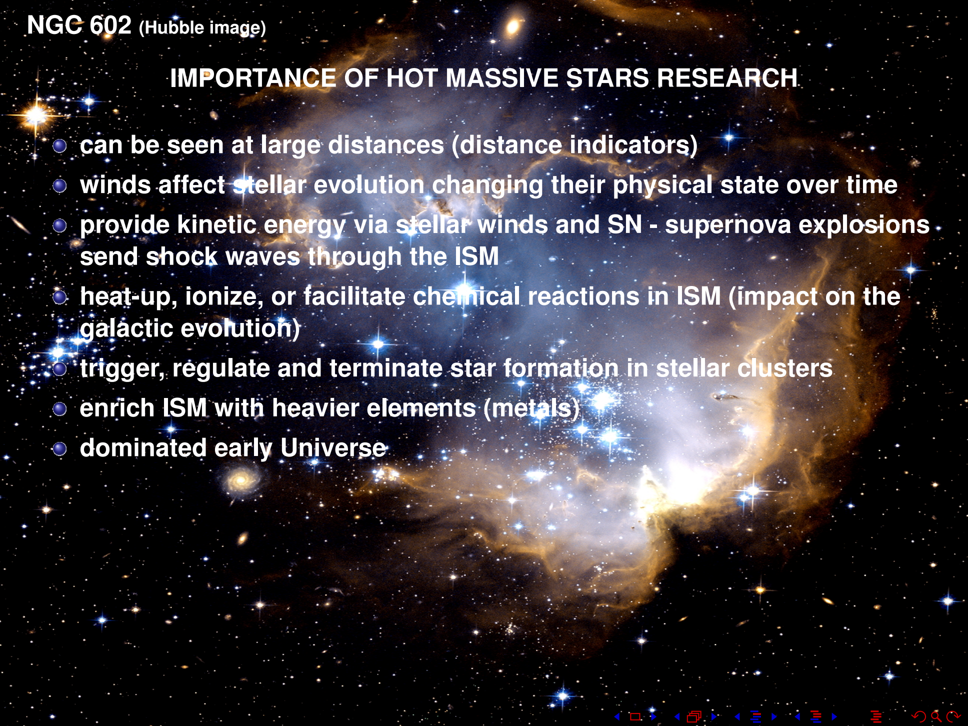

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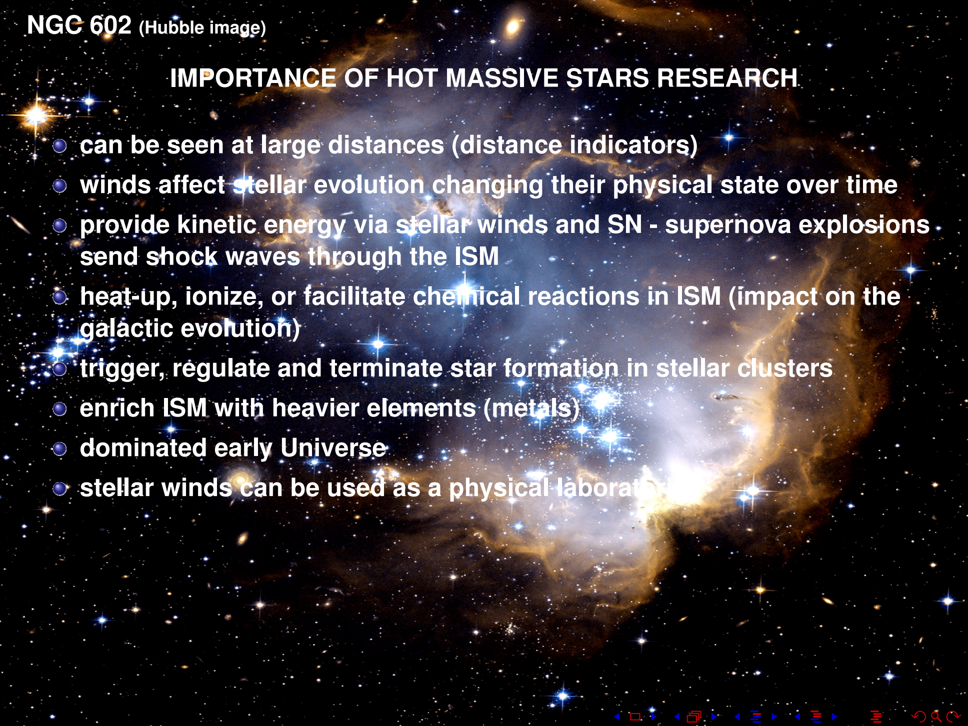

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- dominated early Universe
- stellar winds can be used as a physical laboratories

WHAT IS SIGNATURE OF STELLAR MASS LOSS?

- **Envelopes around stars (nebula)**
  Abell 39 - planetary nebula in the constellation of Hercules

  (created by WIYN/NOAO/NSF)

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  The nebula M1-67 - surrounds Wolf-Rayet star WR 124

  (Hubble image)

WHAT IS SIGNATURE OF STELLAR MASS LOSS?

- **Envelopes around stars (nebula)**
- **Interstellar medium (star clusters)**

PLEIADES - open star cluster containing middle-aged hot B-type stars located in the constellation of Taurus (color-composite image from the Digitized Sky Survey)

WHAT IS SIGNATURE OF STELLAR MASS LOSS?

- **Envelopes around stars (nebula)**
- **Interstellar medium (star clusters)**

M 17 REGION - Omega or Swan Nebula, HII region-molecular cloud. The visible nebula is illuminated by the massive stellar cluster NGC 6618 (ISAAC, VLT ANTU)

WHAT IS SIGNATURE OF STELLAR MASS LOSS?

- **Envelopes around stars (nebula)**
- **Interstellar medium (bubbles, super bubbles)**
  N 70 nebula (in LMC) (FARS2, ESO)

WHAT IS SIGNATURE OF STELLAR MASS LOSS?

- Envelopes around stars (nebula)
- Interstellar medium (star clusters)
- Heavier elements (C, N, O, Fe, . . .)

Crab nebula - expanding remnant of a supernova explosion (Hubble image)

How to release the matter from the surface of the star?

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WHAT IS SIGNATURE OF STELLAR MASS LOSS?

- envelopes around stars (nebula)
- interstellar medium (star clusters)
- heavier elements (C, N, O, Fe, . . .)

Where do heavier elements come from? ⇒ Fusion reactions in stars

How did heavier elements get into the interstellar medium? ⇒ Must be a way in which the stars loss their mass

How to release the matter from the surface of the star?

- spherically symmetric outflow
- equation of motion

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r} = g_e - \frac{1}{\rho}\frac{\partial p}{\partial r} - \frac{GM_*}{r^2}$$

- ρ - density
- v - radial velocity

$$\frac{\mathrm{d}v(r,t)}{\mathrm{d}t} = \frac{\partial v(r,t)}{\partial t} + \underbrace{\frac{\mathrm{d}r(t)}{\mathrm{d}t}}_{v}\frac{\partial v(r,t)}{\partial r}$$

- p - pressure
- g_e - external acceleration

How to release the matter from the surface of the star?

- spherically symmetric outflow
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$$\underbrace{\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r}}_{\text{total acceleration}} = \underbrace{g_e}_{\text{external acceleration}} - \underbrace{\frac{1}{\rho}\frac{\partial p}{\partial r}}_{\text{gas pressure gradient acceleration}} - \underbrace{\frac{GM_*}{r^2}}_{\text{gravitational acceleration}}$$

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How to release the matter from the surface of the star?

- spherically symmetric outflow
- equation of motion - stationary $\partial/\partial(t) = 0$, i.e time-independent

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How to release the matter from the surface of the star?

- spherically symmetric outflow
- equation of motion - stationary $\partial/\partial(t) = 0$, isothermal T(r)=T=const.

$$v\frac{\mathrm{d}v}{\mathrm{d}r} = g_e - \frac{a^2}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r} - \frac{GM_*}{r^2}$$

- ideal gas equation of state

$$p = \frac{k_B T \rho}{m_H \mu} = a^2 \rho$$

- k_B - Boltzmann const.
- m_H - mass of hydrogen
- μ - mean molecular weight per free gas particles
- isothermal speed of sound (const. for isothermal outflow)

$$a = \sqrt{\frac{k_B T}{m_H \mu}}$$

How to release the matter from the surface of the star?

- spherically symmetric outflow
- equation of motion - stationary, isothermal
- integration from R_* to ∞

$$\int_{\mathrm{R}_*}^{\infty} v \frac{\mathrm{d}v}{\mathrm{d}r}\,\mathrm{d}r = \int_{\mathrm{R}_*}^{\infty} g_e\,\mathrm{d}r - \int_{\mathrm{R}_*}^{\infty} \frac{a^2}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r}\,\mathrm{d}r - \int_{\mathrm{R}_*}^{\infty} \frac{GM_*}{r^2}\,\mathrm{d}r$$

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$$\frac{1}{2}v_\infty^2 - \frac{1}{2}v_0^2 = \int_{R_*}^{\infty} g_e \, \mathrm{d}r - a^2 \ln\frac{\rho_\infty}{\rho_0} - \frac{GM_*}{R_*}$$

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- Two cases:
  - if acting force is large enough

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- Two cases:
  - if acting force is large enough
  - sufficiently high initial velocity v_0

$$\frac{1}{2}v_0^2 \geq \frac{GM_*}{\mathrm{R}_*}$$

- condition for energy: $E_\mathrm{k} + E_\mathrm{p} \geq 0$

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- v_{esc} - escape velocity

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$$v_0 \geq v_{\mathrm{esc}} = \sqrt{\frac{2GM_*}{\mathrm{R}_*}}$$

  - v_{esc} - escape velocity
- speed of the particles must be sufficiently large

$$v_{\mathrm{esc}} = 620\,\mathrm{km\,s}^{-1} \left(\frac{M_*}{\mathrm{M}_\odot}\right)^{1/2} \left(\frac{R_*}{\mathrm{R}_\odot}\right)^{-1/2}$$

How to release the matter from the surface of the star?

1. STELLAR WINDS - continuous outflow of particles (neutral or charged gas) ejected from the upper atmosphere of a star
   - CORONAL STELLAR WINDS - driven by gas pressure due to a high temperature of the gas (solar-type stars)
   - DUST DRIVEN STELLAR WINDS (continuum driven winds) - driven by absorption of photons by dust grains (cool luminous stars)
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- MASS-LOSS RATE - $\dot{M}$ $[M_\odot\ yr^{-1}]$
  - Stationary spherically symmetric wind

$$\dot{M} \equiv \frac{\mathrm{d}M_*}{\mathrm{d}t} = 4\pi r^2 \rho(r) \upsilon(r)$$

- TERMINAL VELOCITY - υ_∞ $[\mathrm{km\,s^{-1}}]$ $\upsilon_\infty = \upsilon(r \to \infty)$

Basic wind types and their driving mechanisms

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Halley's Comet

L. Biermann, 1950 - the "corpuscular" radiation from the Sun may play an important role in forming the radially pointing comet tails

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Aurora Borealis

United States Air Force, photo by Senior Airman Joshua Strang

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- EXPERIMENTAL VERIFICATION - observations by LUNA-1,2,3 (1959), VENERA 1 (1961), MARINER II (1962), ULYSSES (1990), SOHO (1995)
  - varies in density, temperature, and speed over time and over longitude
  - two components: the slow solar wind ($v \sim 400\,\mathrm{km\,s^{-1}}$); the fast solar wind ($v \sim 750\,\mathrm{km\,s^{-1}}$)
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WHAT DRIVES THE SOLAR WIND?

GAS PRESSURE DUE TO HIGH TEMPERATURE OF CORONA

Coronal wind

- Root mean square speed of particles of ideal gas

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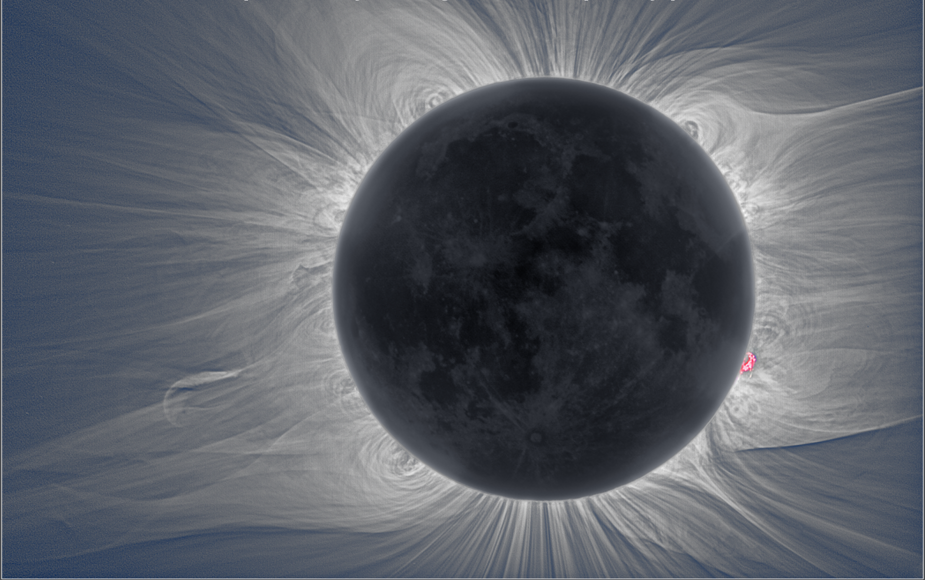
What accelerate particles of the Sun?

CORONA

- observable in optical only during a total eclipse by probes



Total Solar Eclipse 2010

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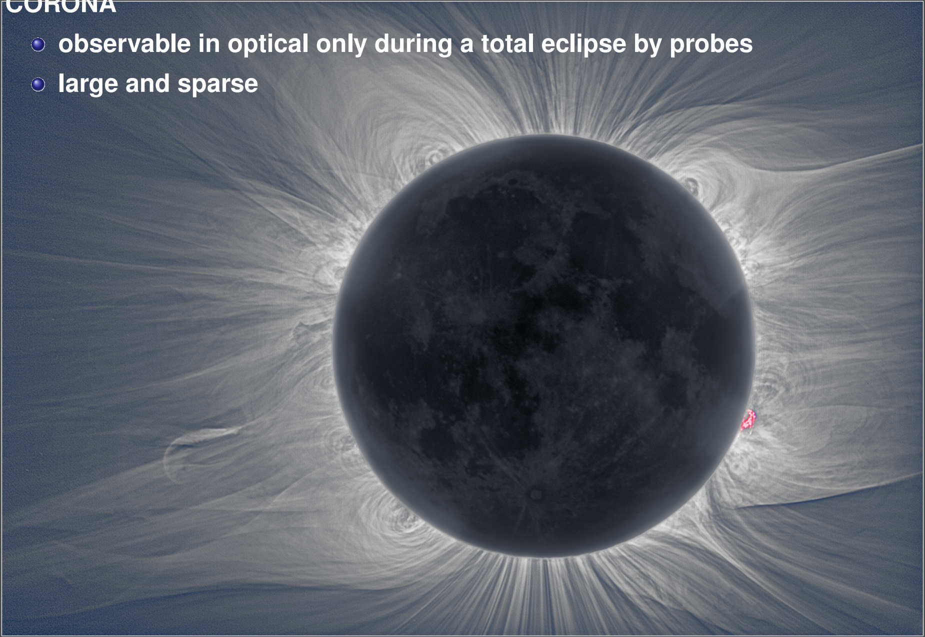

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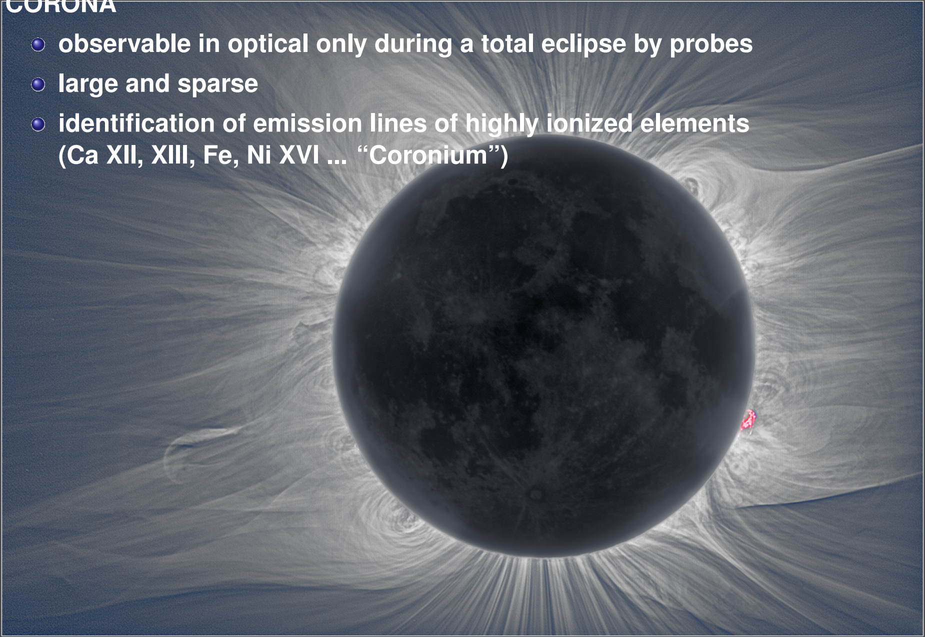
- identification of emission lines of highly ionized elements (Ca XII, XIII, Fe, Ni XVI ... “Coronium”)



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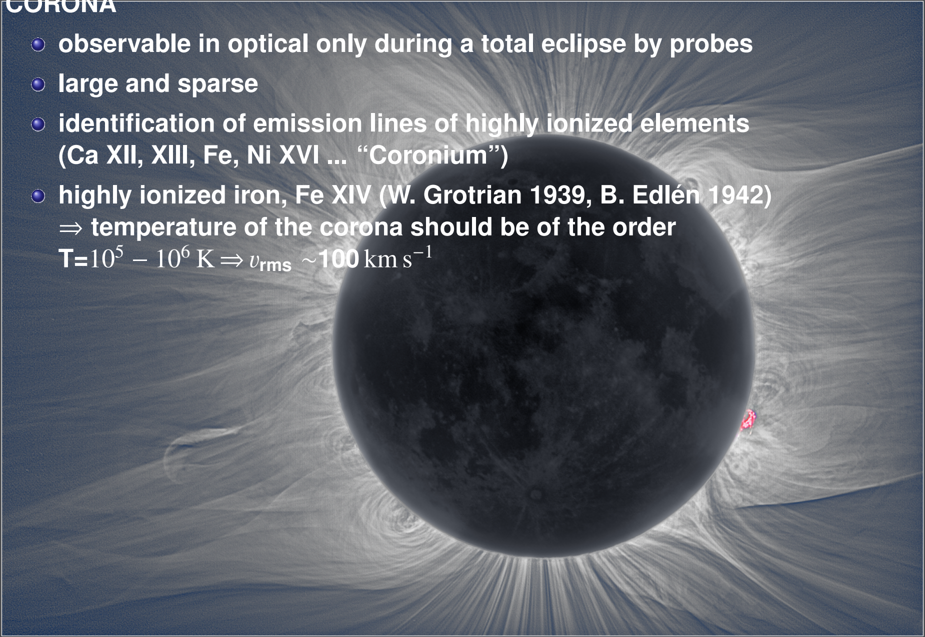
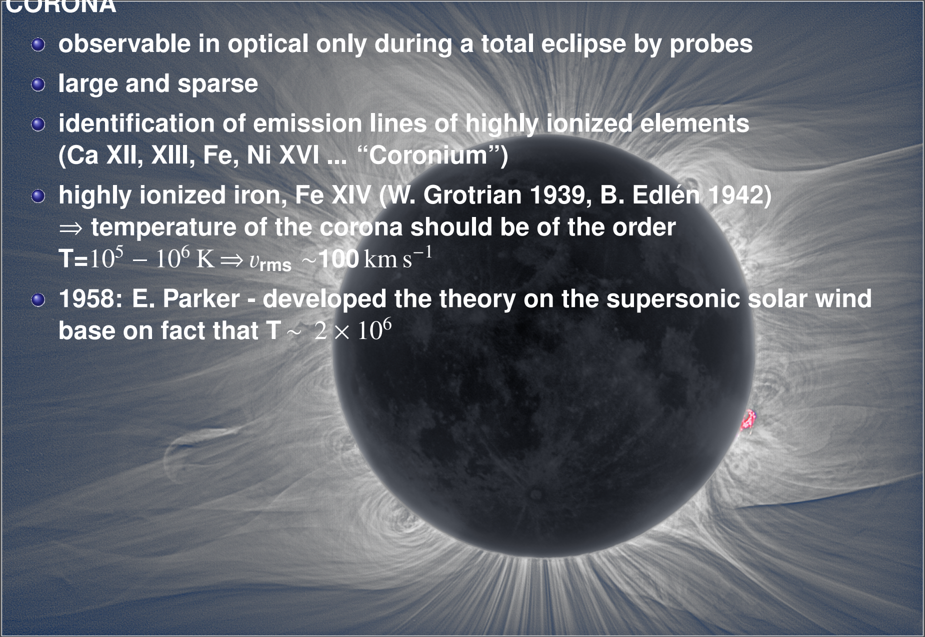


Total Solar Eclipse 2010

CORONA



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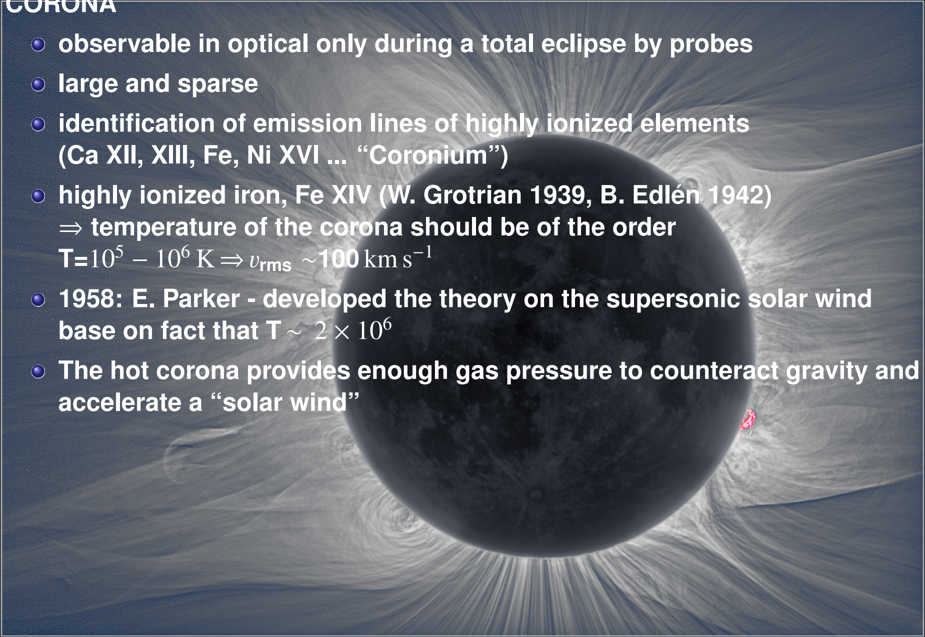

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- Imbalance between the pressure in the outer corona and the local interstellar medium would lead to an expansion of the coronal gas into a supersonic solar wind
- Parker’s solar wind theory has formed the basis for our understanding of the different kinds of the outflows (expanding solar corona, the outflow of ionized gas from galaxies and stars)

Total Solar Eclipse 2010

Parker's solar wind theory

Assumption: isothermal spherically symmetric wind

- The continuity equation

$$\frac{\partial\rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\,\rho\,v) = 0$$

- The equation of motion

$$\rho\,\frac{\partial v}{\partial t} + \rho\,v\frac{\partial v}{\partial r} = -a^2\,\frac{\partial\rho}{\partial r} - \frac{\rho\,GM}{r^2}$$

  - $\rho(r)$ - density
  - $v(r,t)$ - radial velocity
  - a - isothermal speed of sound

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- The equation of motion

$$v\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{a^2}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r} - \frac{GM}{r^2}$$

- density gradient expressed by a velocity gradient (follows from equation of continuity)

$$\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r} = -\frac{1}{v}\frac{\mathrm{d}v}{\mathrm{d}r} - \frac{2}{r}$$

Parker's solar wind theory

Assumption: stationary, isothermal spherically symmetric wind

- The equation of motion

$$\frac{1}{v}(v^2 - a^2)\frac{\mathrm{d}v}{\mathrm{d}r} = \frac{2a^2}{r} - \frac{GM}{r^2}$$

- critical point $\Rightarrow$ $v(r) = a$ or $\mathrm{d}v/\mathrm{d}r = 0$

$$r_{\mathrm{c}} = \frac{GM}{2a^2}$$

- singularity at the point where $v(r) = a$ - sonic point $\Rightarrow$ $\mathrm{d}v/\mathrm{d}r \rightarrow \infty$ or $r = r_c$
- for isothermal wind $r_{\mathrm{c}} > r_0$ (r_0 - bottom of the isothermal region) and the critical point coincides with the sonic point
- The only solution which can have a positive velocity gradient at all distances is the one that goes through the critical point - Critical solution

Parker's solar wind theory

Assumption: stationary, isothermal spherically symmetric wind

- The equation of motion

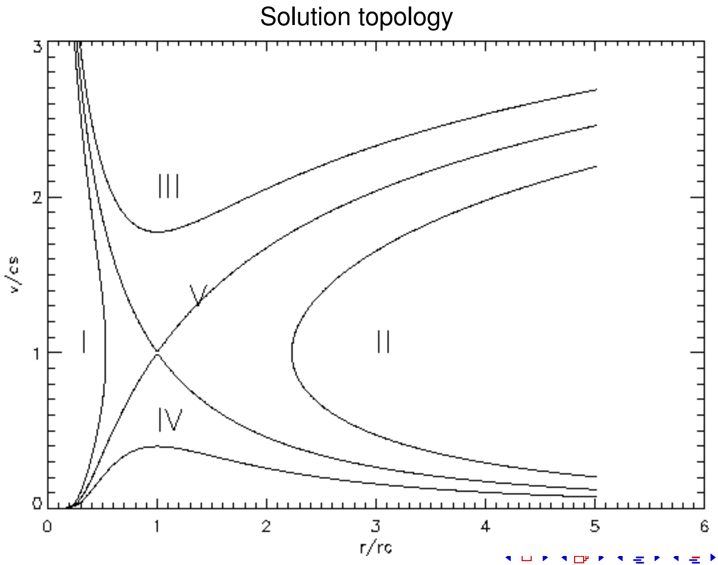
$$\frac{1}{v}(v^2 - a^2)\frac{\mathrm{d}v}{\mathrm{d}r} = \frac{2a^2}{r} - \frac{GM}{r^2}$$

- Direct integration yields the general solution

$$F(r, v) \equiv \frac{v^2}{a^2} - \ln\frac{v^2}{a^2} - 4\,\ln\frac{r}{r_\mathrm{c}} - \frac{4r}{r_\mathrm{c}} = C$$

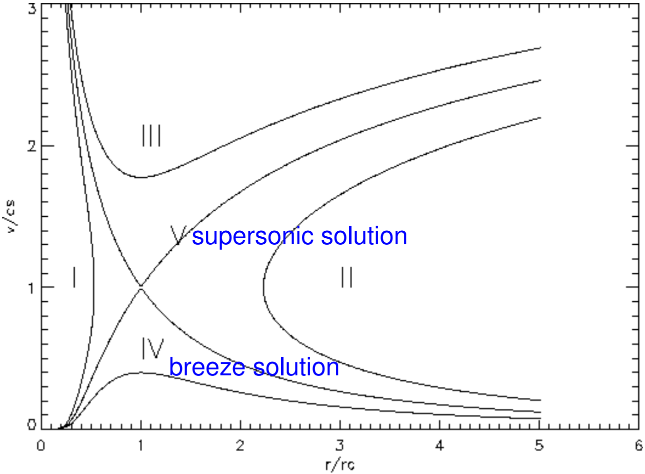
- C - integration constant

Parker’s solar wind theory



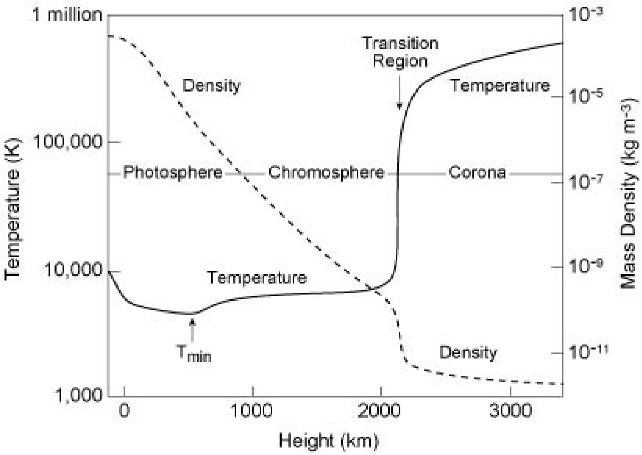
Parker's solar wind theory

Solution topology



Coronal Heating Problem

- Temperature stratification of solar atmosphere



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- Temperature stratification of solar atmosphere
  - the temperature increases very steeply from chromosphere to the corona
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Coronal Heating Problem

- Temperature stratification of solar atmosphere
  - the temperature increases very steeply from chromosphere to the corona
  - corona has very low density $\Rightarrow$ only a small fraction of the total solar radiation is required to power the corona
- How the energy is transported up to the corona, and what mechanism is responsible for the transport?
- several different mechanisms of powering the corona have been proposed:
  - acoustic waves
  - fast and slow magneto-acoustic waves
  - Alfven waves
  - slow and fast magneto-acoustic surface waves
  - current (or magnetic field) dissipation
  - microflares/transients
  - mass/particle flows and magnetic flux emergence
  - "magnetic carpet"
- There is no definite answer to this question yet

Dust driven winds

- Luminous cool stars ($L = 10^4 - 10^6\,\mathrm{L}_\odot$) also have stellar winds. Important for:
  - stars with $0.4\,\mathrm{M}_\odot \lesssim M_0 \lesssim 8\,\mathrm{M}_\odot$ (AGB stars - $L \leq 10^4\,\mathrm{L}_\odot$ and giant)
  - stars with $M_0 \gtrsim 8\,\mathrm{M}_\odot$ (supergiant - $L \leq 10^5\,\mathrm{L}_\odot$)

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- Pulsations contribute to the acceleration
- $v \sim 10 - 30\,\mathrm{km\,s^{-1}}$
- Doppler effect is not important

Dust driven winds

Assumption: isothermal spherically symmetric wind

- The continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v) = 0$$

- The equation of motion

$$\rho \frac{\partial v}{\partial t} + \rho v \frac{\partial v}{\partial r} = -a^2 \frac{\partial \rho}{\partial r} - \frac{\rho G M}{r^2} + \underbrace{\rho g_{\mathrm{rad}}}_{\text{radiation force}}$$

  - $\rho(r)$ - density
  - $v(r,t)$ - radial velocity
  - a - isothermal speed of sound
  - g_{rad} - radiation acceleration

Dust driven winds

Assumption: isothermal spherically symmetric wind, stationary

- The continuity equation

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}(r^2\rho v) = 0$$

- The equation of motion

$$\rho v\frac{\mathrm{d}v}{\mathrm{d}r} = -a^2\frac{\mathrm{d}\rho}{\mathrm{d}r} - \frac{\rho GM}{r^2} + \rho g_{\mathrm{rad}}$$

Dust driven winds

Assumption: stationary, isothermal spherically symmetric wind

- The continuity equation

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}(r^2\rho v) = 0 \quad \Rightarrow \quad \dot{M} \equiv 4\pi r^2 \rho v = \text{const.}$$

Dust driven winds

Assumption: stationary, isothermal spherically symmetric wind

- The equation of motion

$$v\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{a^2}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r} - \frac{GM}{r^2} + g_{\mathrm{rad}}$$

- density gradient expressed by a velocity gradient (equation of continuity)

$$\frac{2}{r} + \frac{1}{v}\frac{\mathrm{d}v}{\mathrm{d}r} + \frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r} = 0$$

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Assumption: stationary, isothermal spherically symmetric wind

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- wind is typically cold, $a^2 \ll GM/r \quad \Rightarrow$ negligible

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  - the radiation force is equal to the gravitational force

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- subsonic wind: $v < a$

$$g_{\mathrm{rad}} < \frac{GM}{r^2}$$

  - the radiation force is lower than the gravitational force (close to the star)

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$$g_{\mathrm{rad}} < \frac{GM}{r^2}$$

- supersonic wind: $v > a$

$$g_{\mathrm{rad}} > \frac{GM}{r^2}$$

  - the radiation force is greater than the gravitational force (far from the star)

Radiation force in presence of dust

Spherically symmetric case

$$f_{\mathrm{rad}} = \rho\, g_{\mathrm{rad}} = \frac{1}{c} \int_{0}^{\infty} \chi(r,\nu)\, F(r,\nu)\, \mathrm{d}\nu$$

- f_{rad} - radiation force
- g_{rad} - radiation acceleration
- $\chi(r,\nu)$ - opacity (absorption coefficient)
- $F(r,\nu)$ - radiation flux

Radiation force in presence of dust

Spherically symmetric case

$$g_{\mathrm{rad}} = \frac{1}{c} \int_0^\infty \kappa(r,\nu)\, F(r,\nu)\, \mathrm{d}\nu$$

- $\kappa = \chi(r,\nu)/\rho$ - changes depending on r only due to changes in the relative concentration of dust

Radiation force in presence of dust

Spherically symmetric case

$$g_{\text{rad}} = \frac{F(r)}{c} \int_0^{\infty} \kappa(r,\nu) \frac{F(r,\nu)}{F(r)} \, \mathrm{d}\nu$$

- $F(r) = \int_0^{\infty} F(r,\nu) \mathrm{d}\nu$ - total radiation flux
- $F(r,\nu)/F(r)$ - depends only on frequency

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- $L = 4\pi r^2 F(r)$

$$g_{\rm rad} = \frac{\bar{\kappa}(r) L}{4\pi r^2 c}$$

Dust driven winds

Assumption: isothermal spherically symmetric wind

- The equation of motion

$$\frac{1}{v}(v^2 - a^2)\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{GM}{r^2} + g_{\mathrm{rad}}$$

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$$\frac{1}{v}(v^2 - a^2)\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{GM}{r^2}\left(1 - \frac{\bar{\kappa}(r)\,L}{4\,\pi\,cGM}\right)$$

$$\Gamma_d(r) = \frac{\bar{\kappa}(r)\,L}{4\,\pi\,cGM}$$

- $\Gamma_d(r)$ - ratio of radiative acceleration and gravity

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$$\Gamma_d(r) = \frac{\bar{\kappa}(r)\,L}{4\,\pi\,cGM}$$

- subsonic part of the wind: $\Gamma_d(r) < 1$
- sonic point: $\Gamma_d(r) = 1$
- supersonic part of the wind: $\Gamma_d(r) > 1$

$\Rightarrow$ close to the star (in the atmosphere) there is a little dust, at larger distances leads to its condensation $\Rightarrow$ $\Gamma_d(r)$ increases with radius

Dust driven winds

The necessary conditions for driving winds with dust

- Transfer of momentum from photons to dust grains.

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- Transfer of momentum from photons to dust grains.
- The momentum coupling between the grains and the gas (drag force). The driving is produced by the drift of the grains through the gas.
  - sets a lower limit on the mass loss rate that can be driven ($10^{-7}\ M_\odot\ yr^{-1}$)
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- Radiation field and T determine whether grains form, and at what distance from the star. Density of the dust forming region determines the mass loss rate of the wind.

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- Radiation field and T determine whether grains form, and at what distance from the star. Density of the dust forming region determines the mass loss rate of the wind.
- Properties of dust opacity determine the transition to supersonic flow and radiative acceleration.

Line-driven winds

AT THE NEXT LECTURE