WINDS OF HOT MASSIVE STARS

I Lecture: Hot massive stars and stellar winds

[1]Brankica Šurlan
[1]Astronomical Institute Ondřejov

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. The radiative force
4. Sobolev approximation
5. Wind hydrodynamics equations
6. Wind instabilities

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
6. The Wind-momentum Luminosity Relation (WLR)

Fourth block

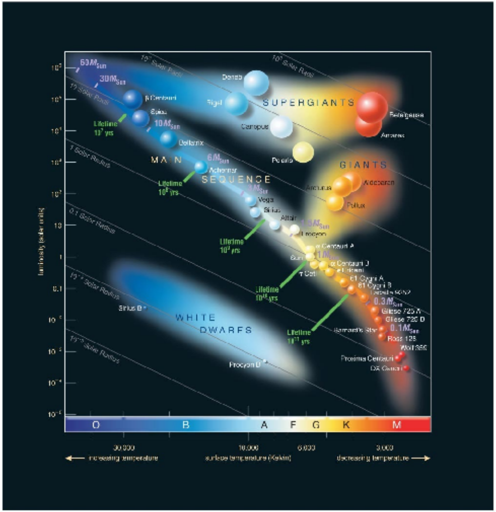
Wind inhomogeneities (clumping)

1. Small and large scale structure
2. Theoretical predictions
3. Observational evidence
4. Theoretical wind-models (parametric description of clumped medium)
5. Influence of clumping on empirical and predicted mass-loss rates
6. Open questions

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 - $T_{\rm eff} \gtrsim 8\,000$ [K]
- MASSIVE - $M \gtrsim 2$ [$M_\odot$]

H-R diagram



Basic properties of hot massive stars

- EXTREMELY LUMINOUS AND BRIGHT
  spectral types A, B, and O
- HOT - $T_{\rm eff} \gtrsim 8\,000$ [K]
- MASSIVE - $M \gtrsim 2$ $[\mathrm{M}_\odot]$

Typical parameters for O-type stars

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

Basic properties of hot massive stars

- EXTREMELY LUMINOUS AND BRIGHT
  spectral types A, B, and O;
  $L \gtrsim 10^2$ [$L_\odot$]
- HOT - $T_{\rm eff} \gtrsim 8\,000$ [K]
- MASSIVE - $M \gtrsim 2$ [$M_\odot$]
- SHORT LIFETIMES
  ($\sim 10^6$ yr)
- END IN SUPERNOVA EXPLOSION
- VERY RARE
- SMALL FRACTION OF THE STELLAR POPULATION

Typical parameters for O-type stars

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

Basic properties of hot massive stars

- EXTREMELY LUMINOUS AND BRIGHT
  spectral types A, B, and O;
  $L \gtrsim 10^2$ [$L_\odot$]
- HOT - $T_{\rm eff} \gtrsim 8\,000$ [K]
- MASSIVE - $M \gtrsim 2\,[M_\odot]$
- SHORT LIFETIMES
  ($\sim 10^6$ yr)
- END IN SUPERNOVA EXPLOSION
- VERY RARE
- SMALL FRACTION OF THE STELLAR POPULATION

Typical parameters for O-type stars

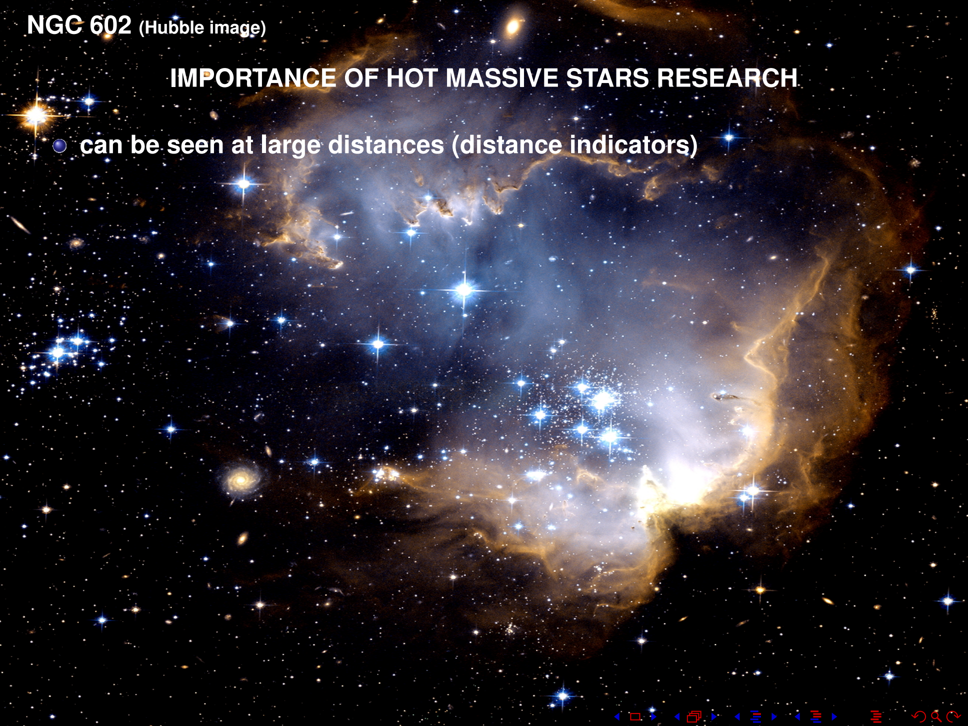
Parameter	Sun	O-type stars
M [$M_\odot$]	1	$\gtrsim 8$
$T_{\rm eff}$[K]	6000	$\gtrsim 30\,000$
L [$L_\odot$]	1	$\sim 10^6$
total life time [yr]	10^{10}	$\sim 10^7$
$T_{\rm wind}$[K]	10^6	$\sim 10^4$
$\dot{M}[M_\odot\ yr^{-1}]$	10^{-14}	$\sim 10^{-6}$
v_∞[km s^{-1}]	400 (700)	$\sim 10^2 - 10^3$

ALL OF THEM LOSE THEIR MASS

NGC 602 (Hubble image)

IMPORTANCE OF HOT MASSIVE STARS RESEARCH

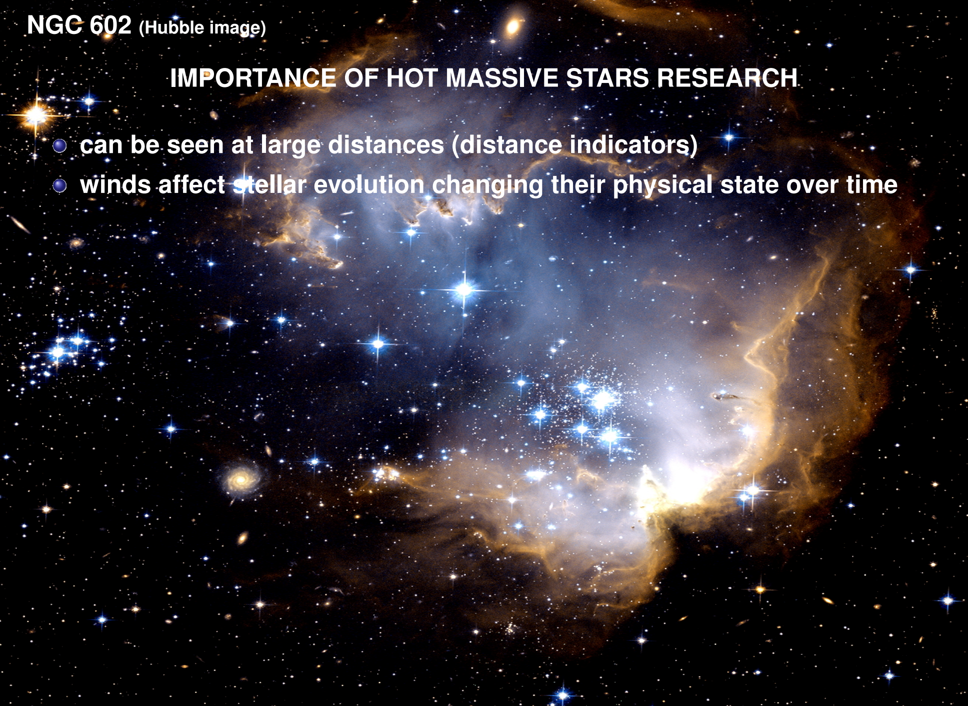
- can be seen at large distances (distance indicators)



NGC 602 (Hubble image)

IMPORTANCE OF HOT MASSIVE STARS RESEARCH

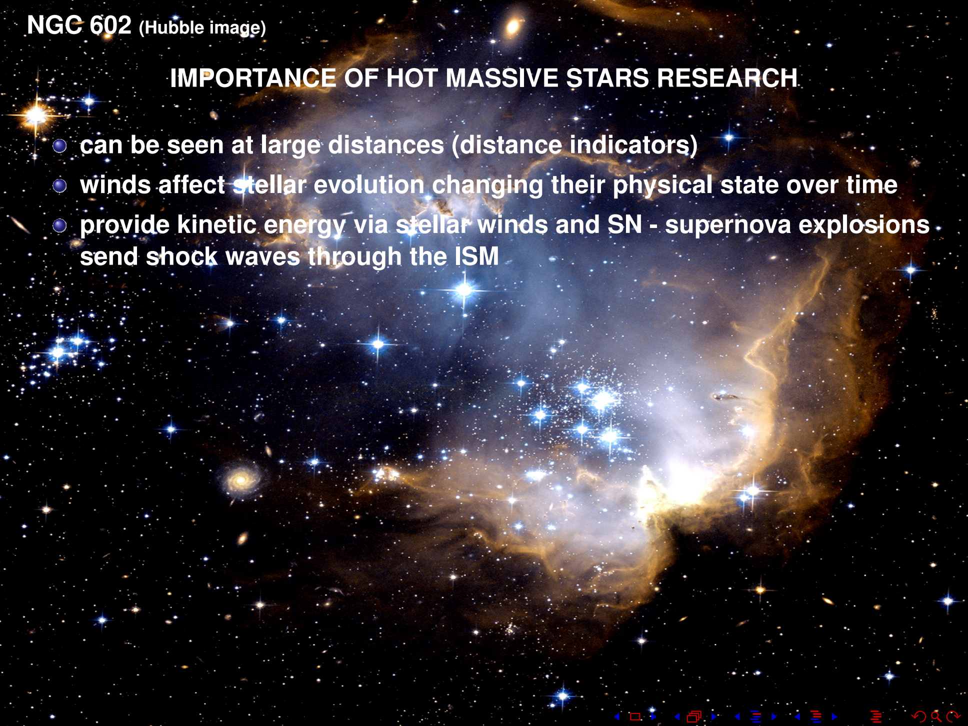
- can be seen at large distances (distance indicators)
- winds affect stellar evolution changing their physical state over time

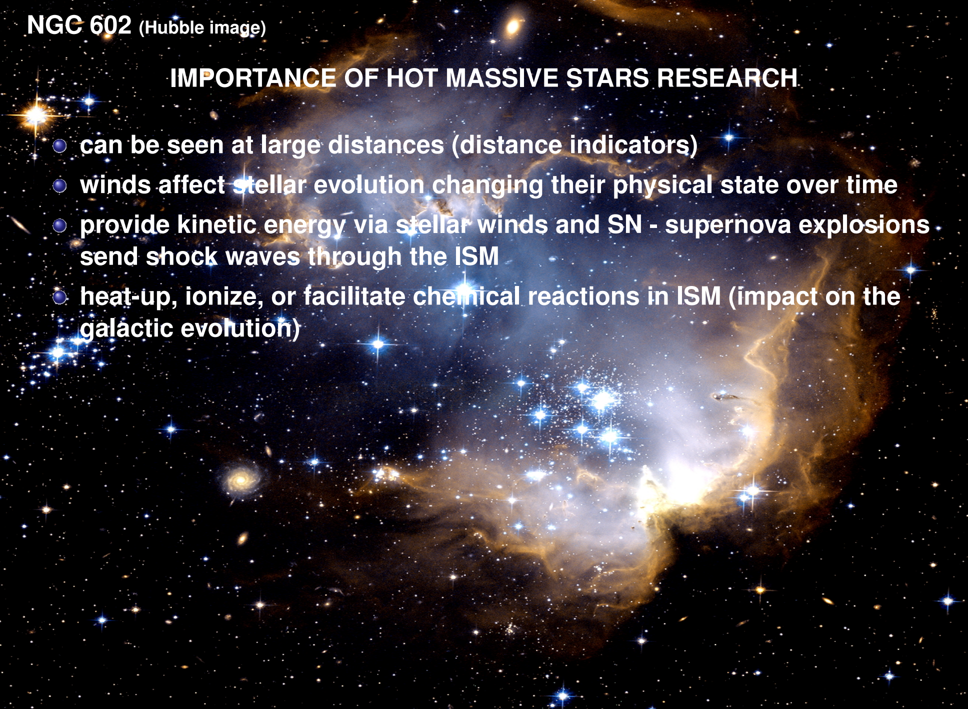


NGC 602 (Hubble image)

IMPORTANCE OF HOT MASSIVE STARS RESEARCH

- can be seen at large distances (distance indicators)
- winds affect stellar evolution changing their physical state over time
- provide kinetic energy via stellar winds and SN - supernova explosions send shock waves through the ISM



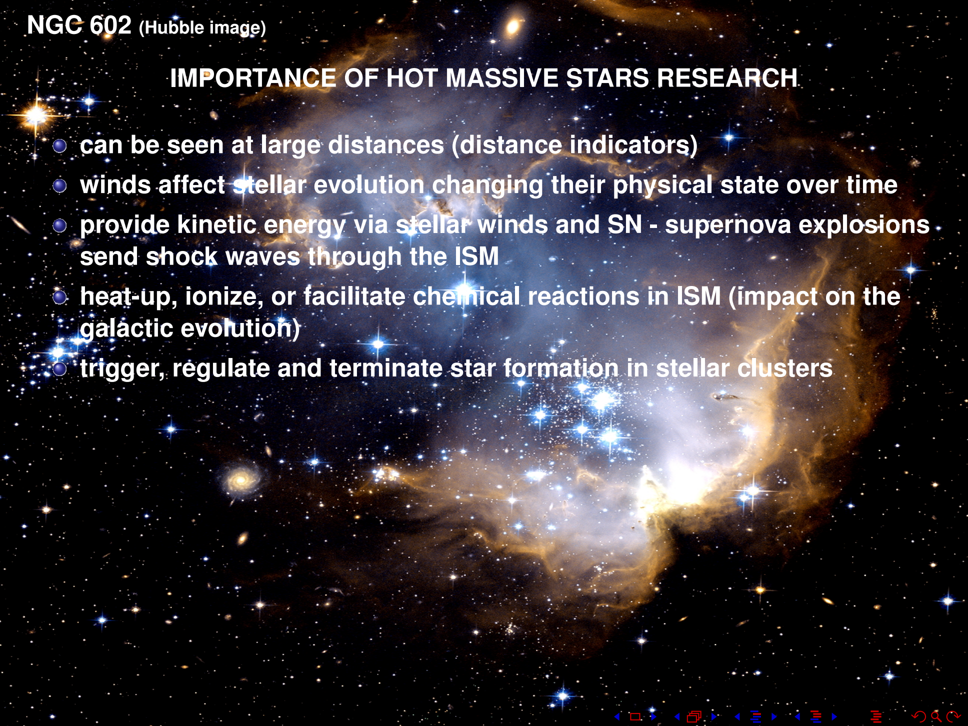


NGC 602 (Hubble image)

IMPORTANCE OF HOT MASSIVE STARS RESEARCH

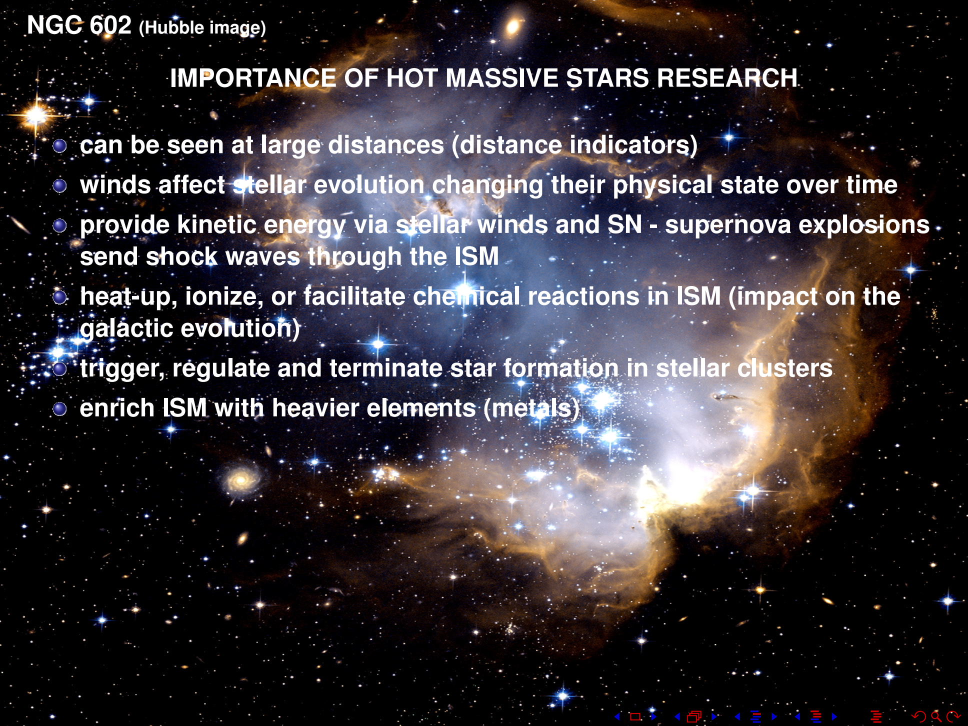
- can be seen at large distances (distance indicators)
- winds affect stellar evolution changing their physical state over time
- provide kinetic energy via stellar winds and SN - supernova explosions send shock waves through the ISM
- heat-up, ionize, or facilitate chemical reactions in ISM (impact on the galactic evolution)

NGC 602 (Hubble image)



IMPORTANCE OF HOT MASSIVE STARS RESEARCH

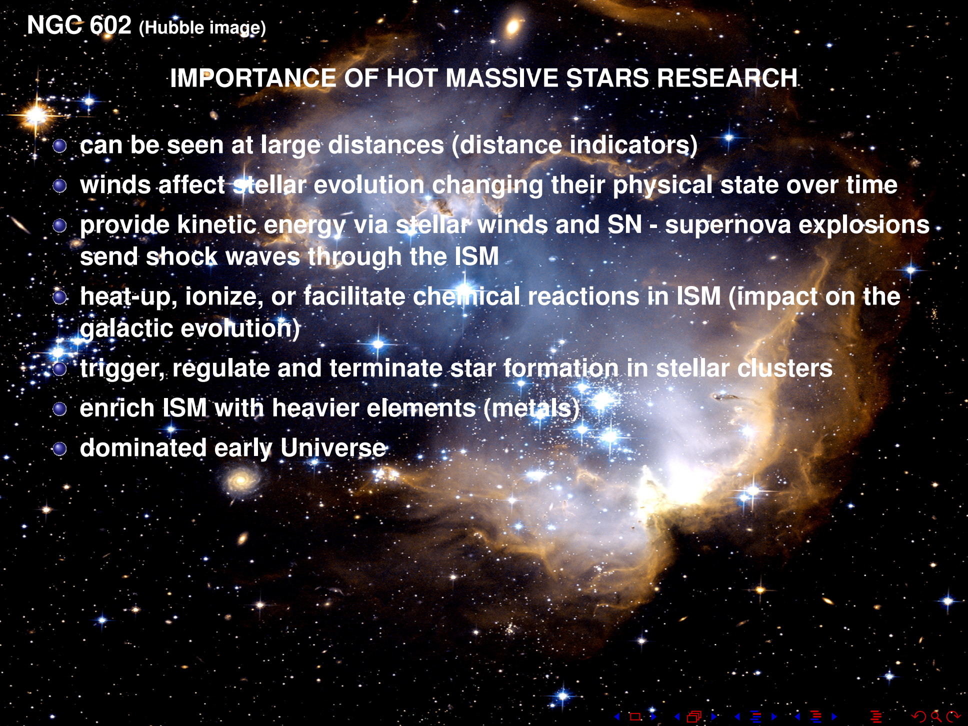
- can be seen at large distances (distance indicators)
- winds affect stellar evolution changing their physical state over time
- provide kinetic energy via stellar winds and SN - supernova explosions send shock waves through the ISM
- heat-up, ionize, or facilitate chemical reactions in ISM (impact on the galactic evolution)
- trigger, regulate and terminate star formation in stellar clusters



NGC 602 (Hubble image)

IMPORTANCE OF HOT MASSIVE STARS RESEARCH

- can be seen at large distances (distance indicators)
- winds affect stellar evolution changing their physical state over time
- provide kinetic energy via stellar winds and SN - supernova explosions send shock waves through the ISM
- heat-up, ionize, or facilitate chemical reactions in ISM (impact on the galactic evolution)
- trigger, regulate and terminate star formation in stellar clusters
- enrich ISM with heavier elements (metals)



NGC 602 (Hubble image)

IMPORTANCE OF HOT MASSIVE STARS RESEARCH

- can be seen at large distances (distance indicators)
- winds affect stellar evolution changing their physical state over time
- provide kinetic energy via stellar winds and SN - supernova explosions send shock waves through the ISM
- heat-up, ionize, or facilitate chemical reactions in ISM (impact on the galactic evolution)
- trigger, regulate and terminate star formation in stellar clusters
- enrich ISM with heavier elements (metals)
- dominated early Universe

NGC 602 (Hubble image)

IMPORTANCE OF HOT MASSIVE STARS RESEARCH

- can be seen at large distances (distance indicators)
- winds affect stellar evolution changing their physical state over time
- provide kinetic energy via stellar winds and SN - supernova explosions send shock waves through the ISM
- heat-up, ionize, or facilitate chemical reactions in ISM (impact on the galactic evolution)
- trigger, regulate and terminate star formation in stellar clusters
- enrich ISM with heavier elements (metals)
- 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)

WHAT IS SIGNATURE OF STELLAR MASS LOSS?

- **Envelopes around stars (nebula)**
  The nebula M1-67 - surrounds Wolf-Rayet star WR 124

  (Hubble image)

WHAT IS SIGNATURE OF STELLAR MASS LOSS?

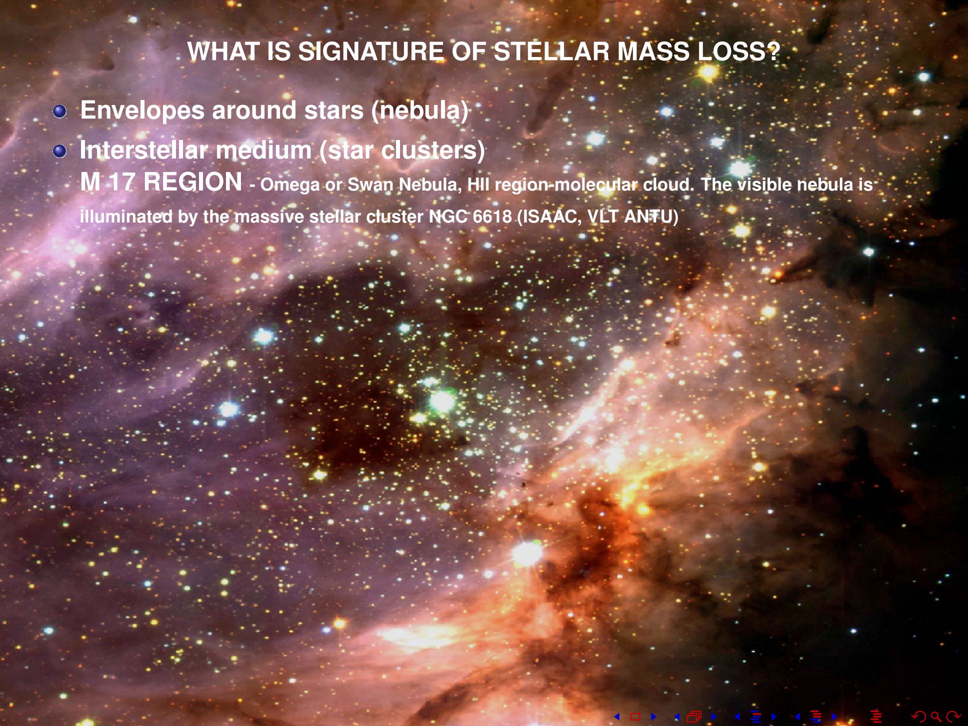
- **Envelopes around stars (nebula)**
- **Interstellar medium (star clusters)**

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?

WHAT IS SIGNATURE OF STELLAR MASS LOSS?

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

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

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
- equation of motion

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

- ρ - density
- v - radial velocity
- p - pressure
- g_e - external acceleration

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

$$\underbrace{\frac{\partial v}{\partial t}}_{\text{cen be neglected}} + v\frac{\partial v}{\partial r} = g_e - \frac{1}{\rho}\frac{\partial p}{\partial r} - \frac{GM_*}{r^2}$$

- ρ - density
- v - radial velocity
- p - pressure

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

- spherically symmetric outflow
- equation of motion - stationary $\partial/\partial(t) = 0$

$$v\frac{\mathrm{d}v}{\mathrm{d}r} = g_e - \frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}r} - \frac{GM_*}{r^2}$$

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 ∞

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

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

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

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

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

- spherically symmetric outflow
- equation of motion - stationary, isothermal $p = a^2\rho$;
- integration from R_* to ∞

$$\frac{1}{2}v_\infty^2 - \frac{1}{2}v_0^2 = \int_{\mathrm{R}_*}^{\infty} g_e \,\mathrm{d}r - \underbrace{\cancel{a^2 \ln \frac{\rho_\infty}{\rho_0}}}_{\text{cen be neglected}} - \frac{GM_*}{\mathrm{R}_*}$$

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

- spherically symmetric outflow
- equation of motion - stationary, isothermal $p = a^2\rho$;
- integration from R_* to ∞

$$\frac{1}{2}v_\infty^2 - \frac{1}{2}v_0^2 = \int_{\mathrm{R}_*}^{\infty} g_e \,\mathrm{d}r - \frac{GM_*}{\mathrm{R}_*}$$

- Two cases:
  - if acting force is large enough

$$\int_{\mathrm{R}_*}^{\infty} g_e \,\mathrm{d}r \geq \frac{GM_*}{\mathrm{R}_*}$$

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

- spherically symmetric outflow
- integration from R_* to ∞

$$\frac{1}{2}v_\infty^2 - \frac{1}{2}v_0^2 = \int_{\mathrm{R}_*}^{\infty} g_e \,\mathrm{d}r - \frac{GM_*}{\mathrm{R}_*}$$

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

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

- spherically symmetric outflow
- integration from R_* to ∞

$$\frac{1}{2}v_\infty^2 - \frac{1}{2}v_0^2 = \int_{\mathrm{R}_*}^{\infty} g_e \,\mathrm{d}r - \frac{GM_*}{\mathrm{R}_*}$$

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

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

- v_{esc} - escape velocity

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

- spherically symmetric outflow
- integration from R_* to ∞

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

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

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

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

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

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)
   - LINE DRIVEN STELLAR WINDS - driven by absorption in spectral lines (hot massive stars)

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)
   - LINE DRIVEN STELLAR WINDS - driven by absorption in spectral lines (hot massive stars)
2. EXPLOSION PROCESSES
   - Supernova explosion
   - Supernova-like explosion (LBV)

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)
   - LINE DRIVEN STELLAR WINDS - driven by absorption in spectral lines (hot massive stars)
2. EXPLOSION PROCESSES
   - Supernova explosion
   - Supernova-like explosion (LBV)

- MASS-LOSS RATE - $\dot{M}$ [$M_\odot$ yr^{-1}]
  - Stationary spherically symmetric wind

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

- TERMINAL VELOCITY - v_∞ $[\mathrm{km\,s^{-1}}]$ $v_\infty = v(r \rightarrow \infty)$

Basic wind types and their driving mechanisms

- CORONAL WINDS - the supersonic outflow of electrically charged particles (mainly electrons and protons) from the solar CORONA

Basic wind types and their driving mechanisms

- CORONAL WINDS - the supersonic outflow of electrically charged particles (mainly electrons and protons) from the solar CORONA
- SIGNATURES

Halley's Comet

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

Basic wind types and their driving mechanisms

- CORONAL WINDS - the supersonic outflow of electrically charged particles (mainly electrons and protons) from the solar CORONA
- SIGNATURES

Aurora Borealis

United States Air Force, photo by Senior Airman Joshua Strang

Basic wind types and their driving mechanisms

- CORONAL WINDS - the supersonic outflow of electrically charged particles (mainly electrons and protons) from the solar CORONA
- 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 ($v \sim 750\ \mathrm{km\,s^{-1}}$)
  - concentration (r= 1 AU) $\sim 10^{-7}$ particles m^{-3}; $\dot{M} \approx 2 \times 10^{-14}\ \mathrm{M_{\odot}\,yr^{-1}}$

Basic wind types and their driving mechanisms

- CORONAL WINDS - the supersonic outflow of electrically charged particles (mainly electrons and protons) from the solar CORONA
- 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 ($v \sim 750\ \mathrm{km\,s^{-1}}$)
  - concentration (r= 1 AU) $\sim 10^{-7}$ particles m^{-3}; $\dot{M} \approx 2 \times 10^{-14}\ \mathrm{M_{\odot}\,yr^{-1}}$

WHAT DRIVES THE SOLAR WIND?

GAS PRESSURE DUE TO HIGH TEMPERATURE OF CORONA

Coronal wind

- Root mean square speed of particles of ideal gas

$$v_{rms} = \sqrt{\frac{3kT}{m_H}}$$

  - T - temperature
  - m_H - the mass of hydrogen

Coronal wind

- Root mean square speed of particles of ideal gas

$$v_{rms} = \sqrt{\frac{3kT}{m_H}}$$

  - T - temperature
  - m_H - the mass of hydrogen
- If $v_{rms} \approx v_{\text{esc}}$ the particles would be able to escape from the surface of the Sun only through their thermal motion

Coronal wind

- Root mean square speed of particles of ideal gas

$$v_{rms} = \sqrt{\frac{3kT}{m_H}}$$

  - T - temperature
  - m_H - the mass of hydrogen
- If $\boxed{v_{rms} \approx v_{\mathrm{esc}}}$ the particles would be able to escape from the surface of the Sun only through their thermal motion
- However, the typical temperature of surface layers of the Sun is 6000 K $\Rightarrow$ $v_{rms} = 12\,\mathrm{km\,s^{-1}} \ll v_{\mathrm{esc}}$

Coronal wind

- Root-mean-square speed of particles of ideal gas

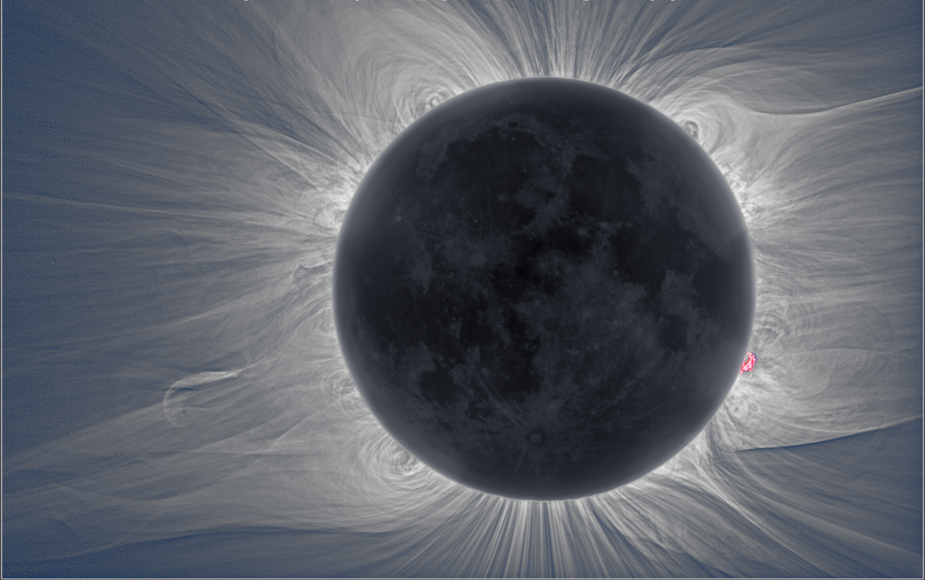
$$v_{rms} = \sqrt{\frac{3kT}{m_H}}$$

  - T - temperature
  - m_H - the mass of hydrogen
- If $v_{rms} \approx v_{\text{esc}}$ the particles would be able to escape from the surface of the Sun only through their thermal motion
- However, the typical temperature of surface layers of the Sun is 6000 K $\Rightarrow$ $v_{rms} = 12\,\text{km}\,\text{s}^{-1} \ll v_{\text{esc}}$

What accelerate particles of the Sun?

CORONA

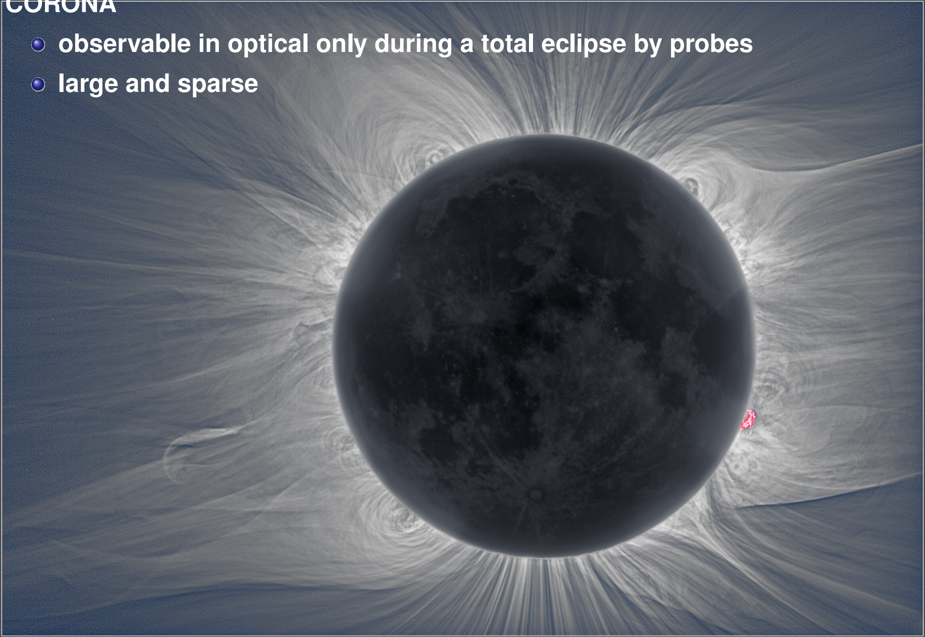
- observable in optical only during a total eclipse by probes



Total Solar Eclipse 2010

CORONA

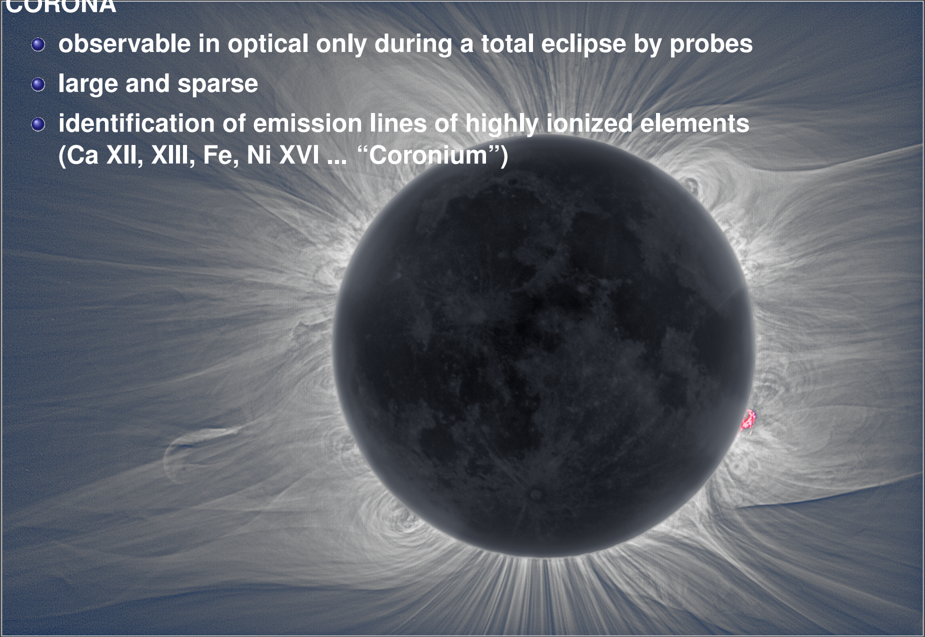
- observable in optical only during a total eclipse by probes
- large and sparse



Total Solar Eclipse 2010

CORONA

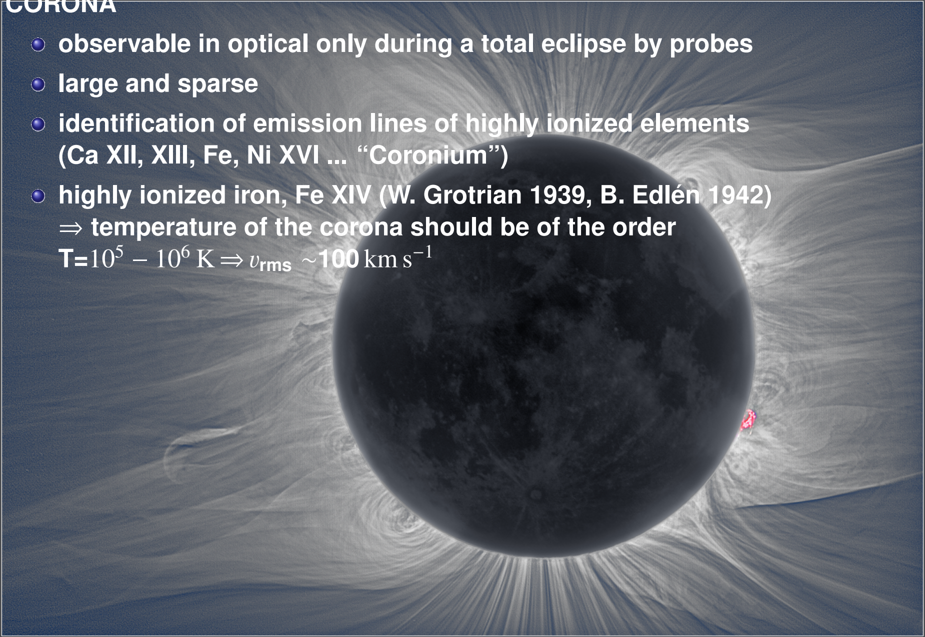
- observable in optical only during a total eclipse by probes
- large and sparse
- identification of emission lines of highly ionized elements (Ca XII, XIII, Fe, Ni XVI ... “Coronium”)



Total Solar Eclipse 2010

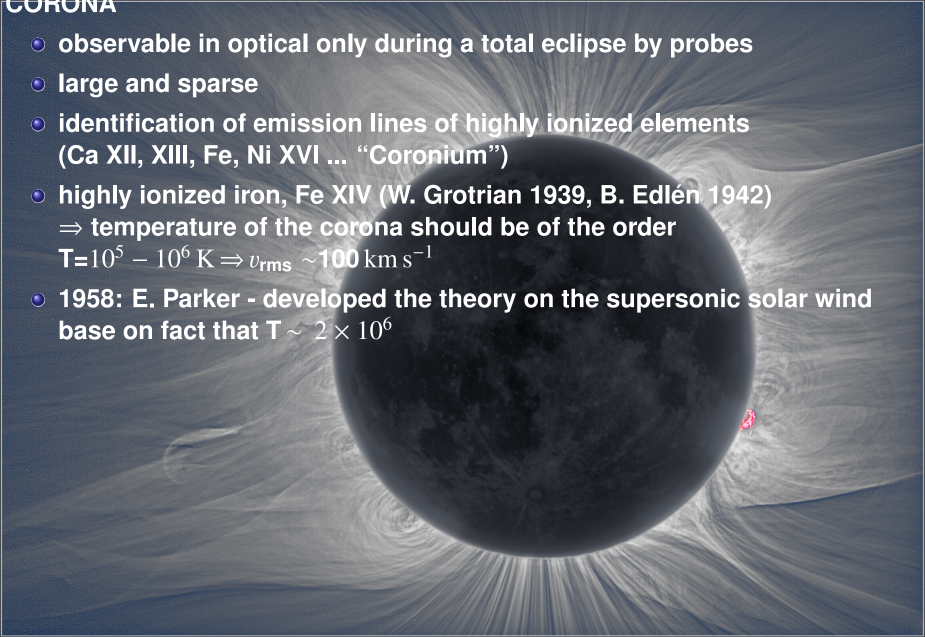
CORONA

- observable in optical only during a total eclipse by probes
- large and sparse
- identification of emission lines of highly ionized elements (Ca XII, XIII, Fe, Ni XVI ... “Coronium”)
- highly ionized iron, Fe XIV (W. Grotrian 1939, B. Edlén 1942) $\Rightarrow$ temperature of the corona should be of the order T=$10^5 - 10^6\,\mathrm{K} \Rightarrow v_{\mathrm{rms}} \sim 100\,\mathrm{km\,s^{-1}}$



Total Solar Eclipse 2010

CORONA

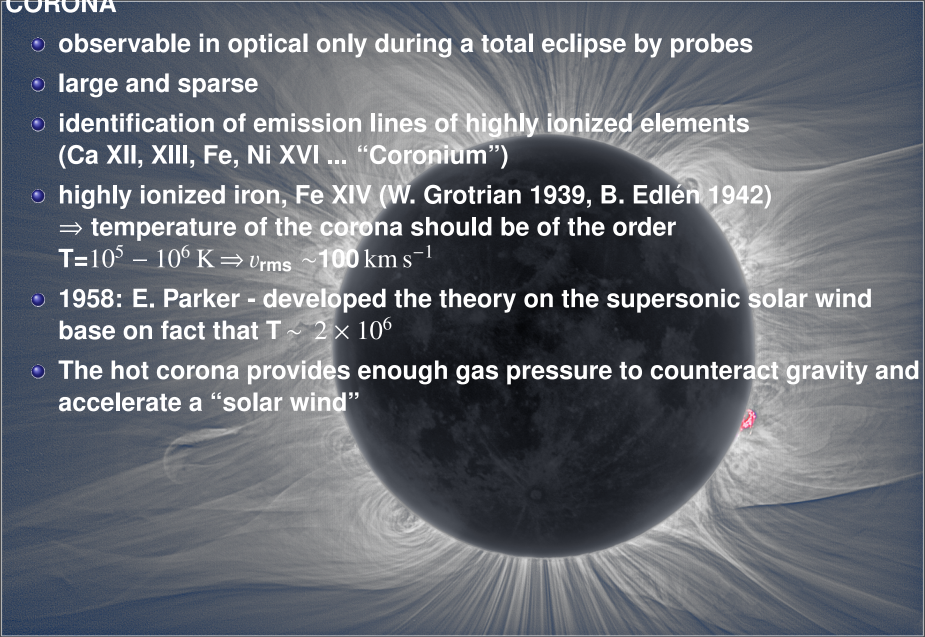


- observable in optical only during a total eclipse by probes
- large and sparse
- identification of emission lines of highly ionized elements (Ca XII, XIII, Fe, Ni XVI ... “Coronium”)
- highly ionized iron, Fe XIV (W. Grotrian 1939, B. Edlén 1942) $\Rightarrow$ temperature of the corona should be of the order T=$10^5 - 10^6$ K $\Rightarrow v_{\mathrm{rms}} \sim 100$ km s^{-1}
- 1958: E. Parker - developed the theory on the supersonic solar wind base on fact that T $\sim 2 \times 10^6$

Total Solar Eclipse 2010

CORONA

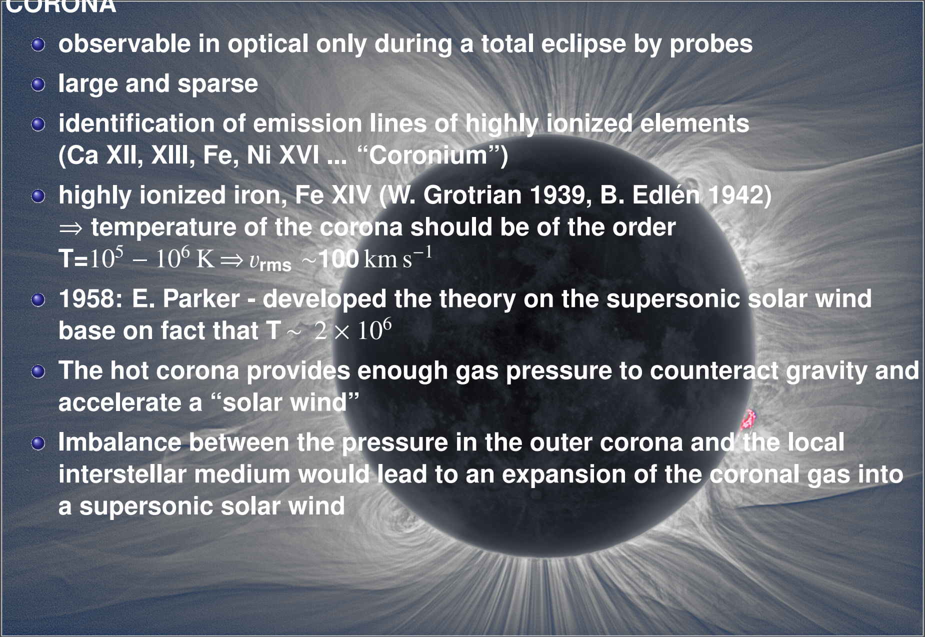
- observable in optical only during a total eclipse by probes
- large and sparse
- identification of emission lines of highly ionized elements (Ca XII, XIII, Fe, Ni XVI ... “Coronium”)
- highly ionized iron, Fe XIV (W. Grotrian 1939, B. Edlén 1942)
  $\Rightarrow$ temperature of the corona should be of the order
  T=$10^5 - 10^6$ K $\Rightarrow v_{\mathrm{rms}} \sim 100$ km s^{-1}
- 1958: E. Parker - developed the theory on the supersonic solar wind base on fact that T $\sim 2 \times 10^6$
- The hot corona provides enough gas pressure to counteract gravity and accelerate a “solar wind”



Total Solar Eclipse 2010

CORONA

- observable in optical only during a total eclipse by probes
- large and sparse
- identification of emission lines of highly ionized elements (Ca XII, XIII, Fe, Ni XVI ... “Coronium”)
- highly ionized iron, Fe XIV (W. Grotrian 1939, B. Edlén 1942) $\Rightarrow$ temperature of the corona should be of the order T=$10^5 - 10^6$ K $\Rightarrow v_{\mathrm{rms}} \sim 100$ km s^{-1}
- 1958: E. Parker - developed the theory on the supersonic solar wind base on fact that T $\sim 2 \times 10^6$
- The hot corona provides enough gas pressure to counteract gravity and accelerate a “solar wind”
- 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



Total Solar Eclipse 2010

CORONA

- large and sparse
- identification of emission lines of highly ionized elements (Ca XII, XIII, Fe, Ni XVI ... “Coronium”)
- highly ionized iron, Fe XIV (W. Grotrian 1939, B. Edlén 1942) $\Rightarrow$ temperature of the corona should be of the order T=$10^5 - 10^6$ K $\Rightarrow v_{\mathrm{rms}} \sim 100\,\mathrm{km\,s^{-1}}$
- 1958: E. Parker - developed the theory on the supersonic solar wind base on fact that T $\sim 2 \times 10^6$
- The hot corona provides enough gas pressure to counteract gravity and accelerate a “solar wind”
- 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)

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

Parker's solar wind theory

Assumption: stationary, isothermal spherically symmetric wind

- The continuity equation

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

- The equation of motion

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

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

Parker's solar wind theory

Assumption: stationary, isothermal spherically symmetric wind

- The continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v) = 0 \quad \Rightarrow \quad \dot{M} \equiv 4\pi r^2 \rho v$$

Parker's solar wind theory

Assumption: stationary, isothermal spherically symmetric wind

- The equation of motion

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

- 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

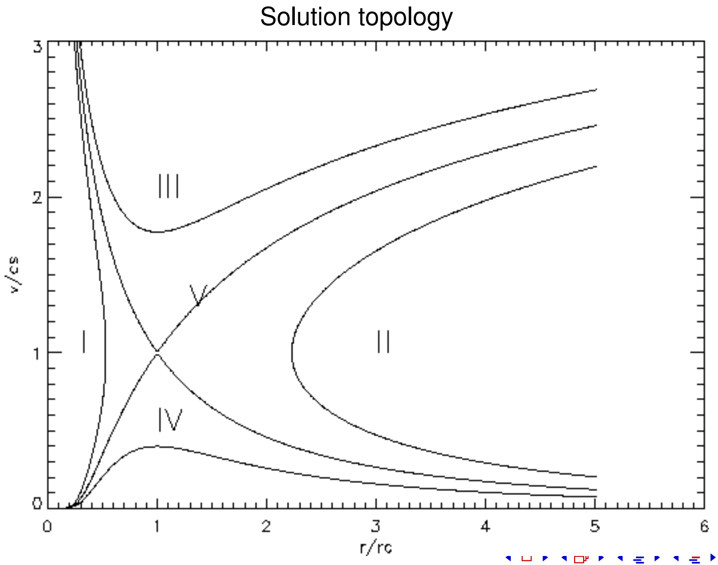
$$\frac{1}{v}\left(v^2 - a^2\right)\frac{\mathrm{d}v}{\mathrm{d}r} = \frac{2a^2}{r} - \frac{GM}{r^2}$$

- Direct integration yields the general solution

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

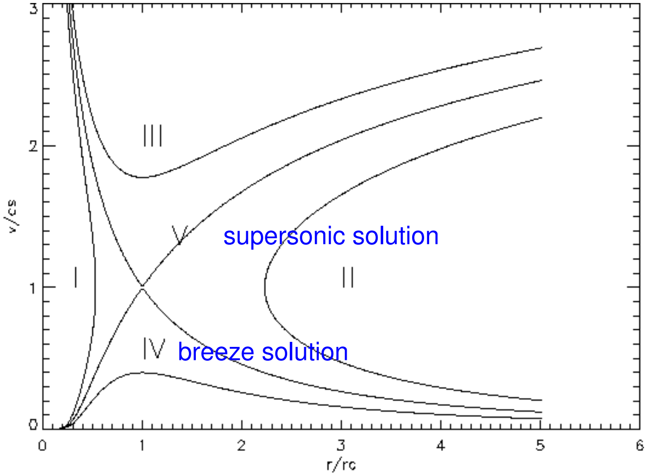
- C - integration constant

Parker's solar wind theory



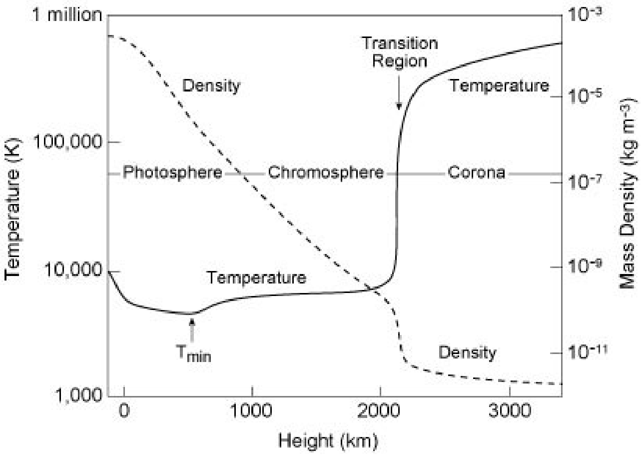
Parker's solar wind theory

Solution topology



Coronal Heating Problem

- Temperature stratification of solar atmosphere



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

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 that 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 - $L \leq 10^5\,\mathrm{L}_\odot$)

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 - $L \leq 10^5\,\mathrm{L}_\odot$)
- Stars have high luminosities $\Rightarrow$ the outer atmosphere can be driven by strong radiation field from the stellar surface

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 - $L \leq 10^5\,\mathrm{L}_\odot$)
- Stars have high luminosities $\Rightarrow$ the outer atmosphere can be driven by strong radiation field from the stellar surface
- Radiative driving occurs because of absorption of photons by dust grains that can form in the outer atmosphere

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 - $L \leq 10^5\,\mathrm{L}_\odot$)
- Stars have high luminosities $\Rightarrow$ the outer atmosphere can be driven by strong radiation field from the stellar surface
- Radiative driving occurs because of absorption of photons by dust grains that can form in the outer atmosphere
- Radiation force due to the absorption of radiation on dust particles can accelerate the wind -“Continuum driven wind”

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 - $L \leq 10^5\,\mathrm{L_\odot}$)
- Stars have high luminosities $\Rightarrow$ the outer atmosphere can be driven by strong radiation field from the stellar surface
- Radiative driving occurs because of absorption of photons by dust grains that can form in the outer atmosphere
- Radiation force due to the absorption of radiation on dust particles can accelerate the wind -“Continuum driven wind”
- Pulsations contribute to the acceleration

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 - $L \leq 10^5\,\mathrm{L_\odot}$)
- Stars have high luminosities $\Rightarrow$ the outer atmosphere can be driven by strong radiation field from the stellar surface
- Radiative driving occurs because of absorption of photons by dust grains that can form in the outer atmosphere
- Radiation force due to the absorption of radiation on dust particles can accelerate the wind -“Continuum driven wind”
- Pulsations contribute to the acceleration
- $v \sim 10 - 30\,\mathrm{km\,s^{-1}}$

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 - $L \leq 10^5\,\mathrm{L}_\odot$)
- Stars have high luminosities $\Rightarrow$ the outer atmosphere can be driven by strong radiation field from the stellar surface
- Radiative driving occurs because of absorption of photons by dust grains that can form in the outer atmosphere
- Radiation force due to the absorption of radiation on dust particles can accelerate the wind -“Continuum driven wind”
- 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

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

  - $\rho(r)$ - 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

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

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)

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

Dust driven winds

Assumption: stationary, isothermal spherically symmetric wind

- The equation of motion

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

Dust driven winds

Assumption: stationary, isothermal spherically symmetric wind

- The equation of motion

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

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

Dust driven winds

Assumption: stationary, isothermal spherically symmetric wind

- The equation of motion

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

- sound point: $v = a$

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

  - the radiation force is equal to the gravitational force

Dust driven winds

Assumption: stationary, isothermal spherically symmetric wind

- The equation of motion

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

- sound point: $v = a$

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

- subsonic wind: $v < a$

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

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

Dust driven winds

Assumption: stationary, isothermal spherically symmetric wind

- The equation of motion

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

- sound point: $v = a$

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

- subsonic wind: $v < a$

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

- 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

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

- 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

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

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

Radiation force in presence of dust

Spherically symmetric case

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

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

Radiation force in presence of dust

Spherically symmetric case

$$g_{\text{rad}} = \frac{F(r)}{c} \underbrace{\int_0^\infty \kappa(r,\nu) \frac{F(r,\nu)}{F(r)} \mathrm{d}\nu}_{\text{flux mean opacity } \bar{\kappa}(\text{r})}$$

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

$$g_{\text{rad}} = \frac{1}{c} \bar{\kappa}(r) F(r)$$

Radiation force in presence of dust

Spherically symmetric case

$$g_{\text{rad}} = \frac{F(r)}{c} \underbrace{\int_0^\infty \kappa(r,\nu) \frac{F(r,\nu)}{F(r)} \mathrm{d}\nu}_{\text{flux mean opacity } \bar{\kappa}(r)}$$

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

$$g_{\text{rad}} = \frac{1}{c}\,\bar{\kappa}(r)F(r)$$

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

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

Dust driven winds

Assumption: isothermal spherically symmetric wind

- The equation of motion

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

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

Dust driven winds

Assumption: isothermal spherically symmetric wind

- The equation of motion

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

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

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

Dust driven winds

Assumption: isothermal spherically symmetric wind

- The equation of motion

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

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

- subsonic wind: $\Gamma_d(r) < 1$
- sonic point: $\Gamma_d(r) = 1$
- supersonic 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.

Dust driven winds

The necessary conditions for driving winds with dust

- 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 $(10^{-7}\,M_{\odot}\,yr^{-1})$
    - sets a limit to the speed of a dust driven wind

Dust driven winds

The necessary conditions for driving winds with dust

- 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 ($10^{-7}\ M_\odot\ yr^{-1}$)
  - sets a limit to the speed of a dust driven wind
- The transition to supersonic flow does not occur very close to the star. There is a dust free extended photospheric region which lies below the dust condensation radius.

Dust driven winds

The necessary conditions for driving winds with dust

- 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 ($10^{-7}\,M_{\odot}\,yr^{-1}$)
  - sets a limit to the speed of a dust driven wind
- The transition to supersonic flow does not occur very close to the star. There is a dust free extended photospheric region which lies below the dust condensation radius.
- 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.

Dust driven winds

The necessary conditions for driving winds with dust

- 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 ($10^{-7}\, M_\odot\, yr^{-1}$)
  - sets a limit to the speed of a dust driven wind
- The transition to supersonic flow does not occur very close to the star. There is a dust free extended photospheric region which lies below the dust condensation radius.
- 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.