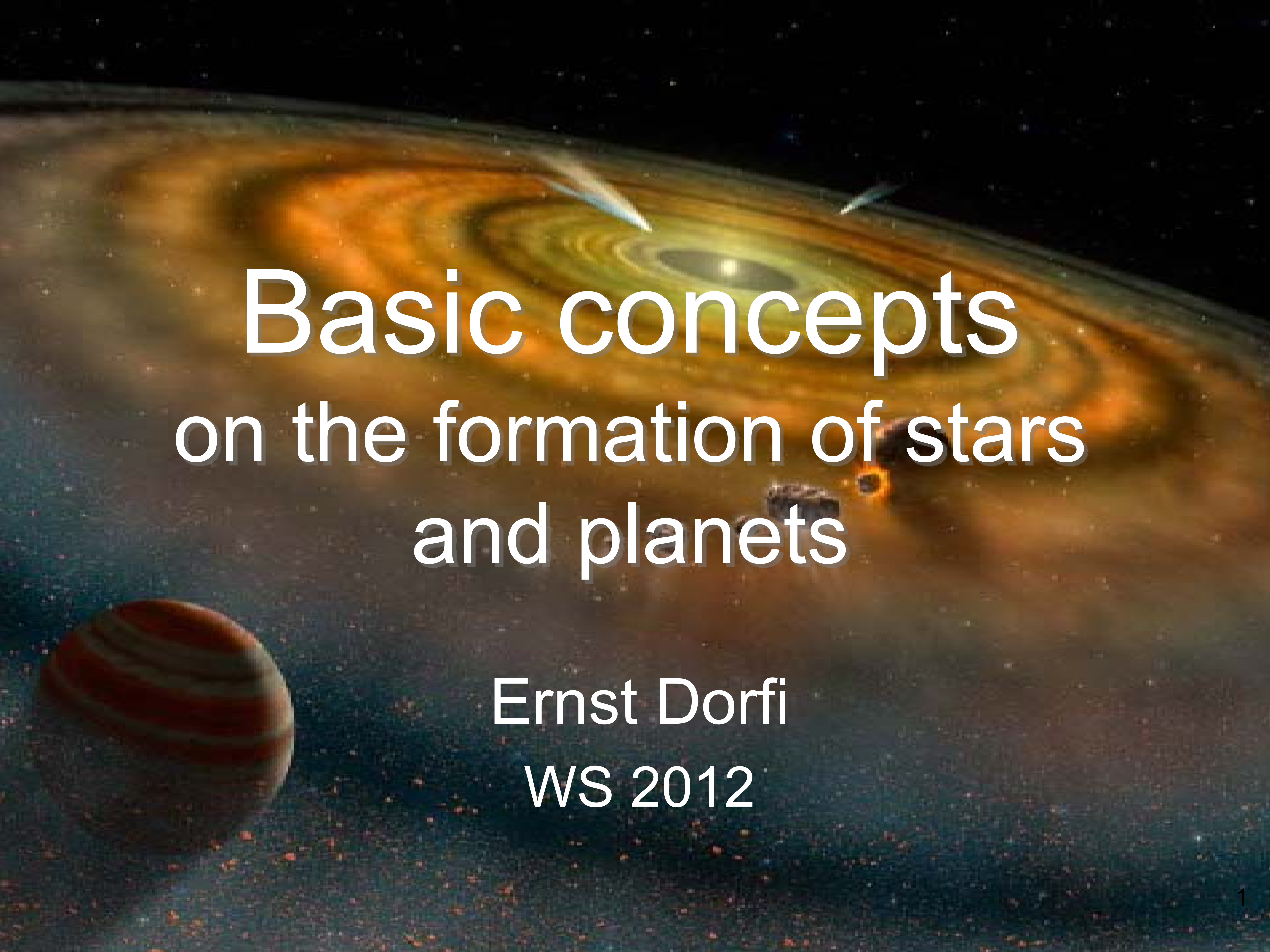


Basic concepts

on the formation of stars and planets

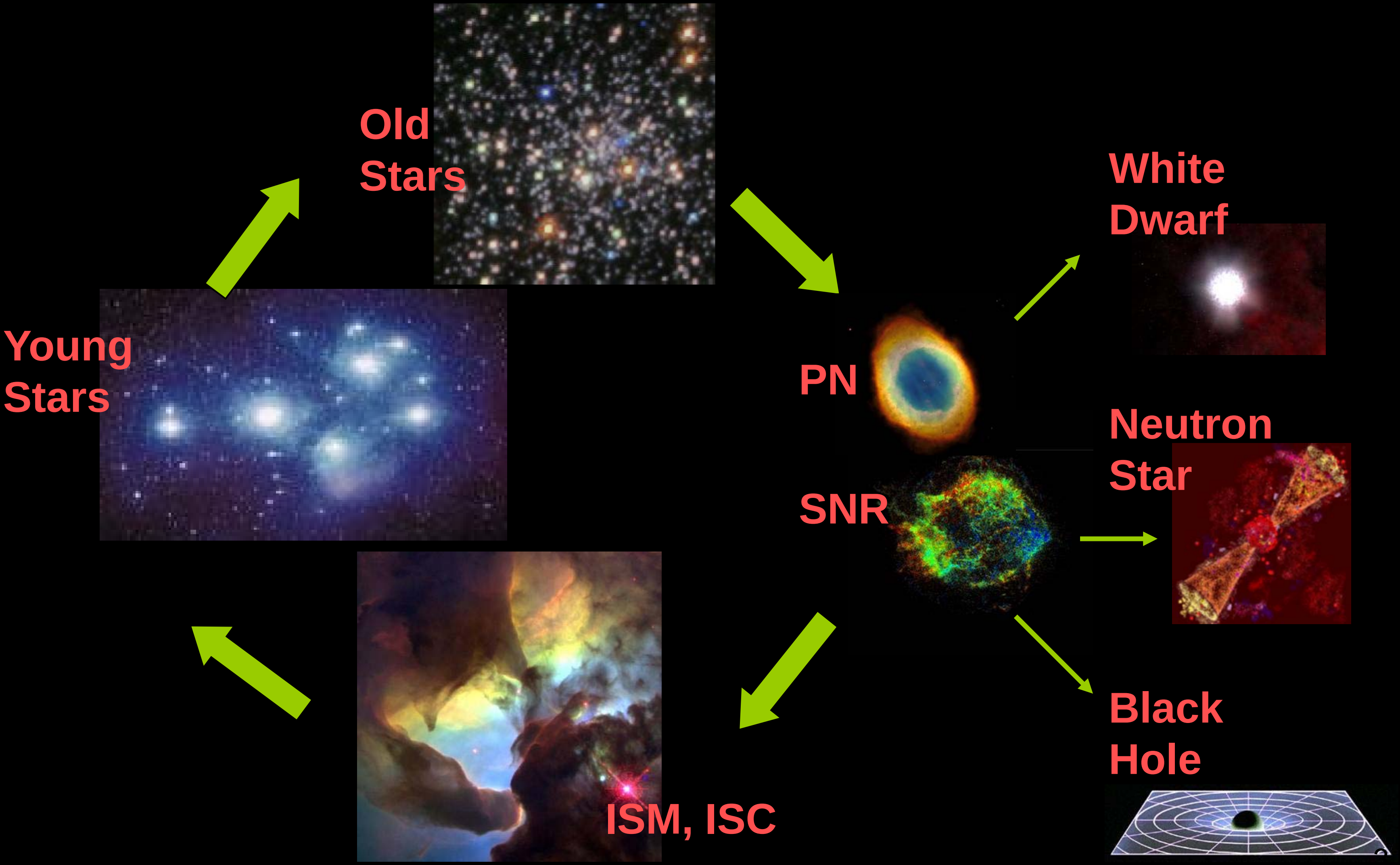
Ernst Dorfi

WS 2012

Remarks on …

- Interstellar Medium
- Gravitational collapse
- Formation of protostars and disks
- Observational evidence of extrasolar planets

Recycling of Mater



Old Stars

White Dwarf

Young Stars

PN

Neutron Star

SNR

Black Hole

ISM, ISC

Components of the ISM

- **Gas and dust:** several phases with different densities and temperatures
- **Radiation fields:** large local variations, ionization, absorption
- **Velocity fields:** large scale flows as well as turbulent small scale motions
- **Magnetic fields:** large scale ordered as well as turbulent components
- **Cosmic rays:** high energy particles with energies beyond the thermal velocities, provide pressure

➡ **All have comparable energy densities: ~ 1eV/cm^3**

ISM: Summary

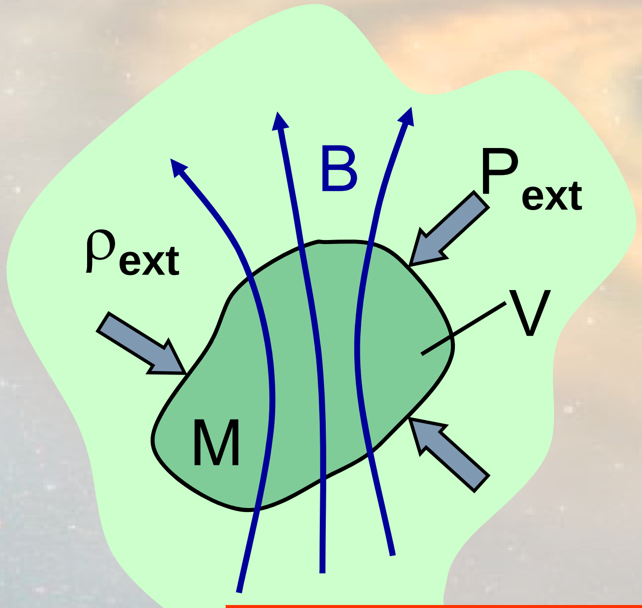
- ISM is highly inhomogeneous and consists of several phases, e.g. gas temperatures between 10K and 10^6K
- Mass of ISM in our Galaxy around $10^9 M_\odot$
- Most of the mass in the cold phase, most of the volume occupied by hot gas
- Energy densities of all components (gas, radiation, motions, magnetic fields, cosmic rays) are comparable: ~1eV/cm^3
- Pressure in our Galaxy: $P \sim nT \sim 3000\,\mathrm{cm}^{-3}\mathrm{K}$ with large local deviations, e.g. HII-Regions, shocks, SNR, ...
- Sources of ISM: Stellar winds, SN-explosions, infall from the galactic halo or the intergalactic medium
- Sinks des ISM: star formation, accretion, galactic winds

→ Masses of disks and planets are negligible

Star formation

- **Fragmentation:** mass of interstellar clouds (ISC) » mass of individual stars
- Virial theorem: no smooth transitions possible, highly non-linear process
- Minimal mass of gravitational unstable fragments determined by energy losses, transition from isothermal to adiabatic contraction
- **Magnetic braking:** loss of angular momentum by magnetic tension, necessary to overcome centrifugal barrier
- **Angular momentum:** Formation of protostellar disks, gravitational settling of dust particles onto the equatorial plane, formation of planets within these disks

Virial Theorem



- Important tool to characterize global properties of equilibrium configurations without detailed knowledge of interior structure
- Relation between different energies: derivation through scalar multiplication of the equation of motion followed by an integration over a finite volume

$$\frac{d^2I}{dt^2} = 2E_{\text{kin}} + 3(\gamma-1)E_{\text{therm}} + E_{\text{mag}} + E_{\text{grav}} + S$$

moment of inertia
thermal energy
gravitational energy

kinetic energy
magnetic energy
surface terms

Collapse time scale

Time scale of collapse: τ

Simplified Virialtheorem: Change of the moment of inertia only by gravitational forces

$$\boxed{\frac{MR^2}{\tau^2} \simeq \frac{GM^2}{R}}$$

Mass is kept constant, divide by R^2

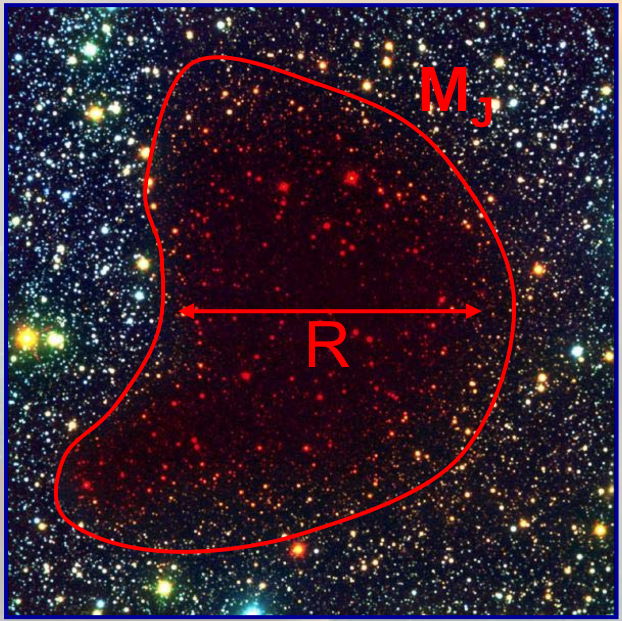
$$\boxed{\frac{1}{\tau^2} \simeq \frac{GM}{R^3} \simeq G\rho}$$

Time scale τ depends only on the mean density of the collapsing region

$$\boxed{\tau \simeq \frac{1}{\sqrt{G\rho}}}$$

→ ***free-fall-time:*** around 10^6 years

Jeans - Mass



ESO/VLT: B68, IR

Collaps time scale, free-fall-time: $$t_{\mathrm{ff}} \propto (G\rho)^{-1/2}$$

Sound velocity: $$c_{\mathrm{s}} = \sqrt{\frac{\gamma P}{\rho}} \propto T^{1/2}$$

Sound crossing time: $$\frac{R}{c_{\mathrm{s}}} \simeq t_{\mathrm{ff}}$$

typical length scale: $$R \propto \rho^{-1/2} T^{1/2}$$

typcial mass: $$M_{\mathrm{J}} \propto \rho R^3 \propto \rho^{-1/2} T^{3/2}$$

Minimal mass of perturbation: **Jeans mass**

$M_J \downarrow$ if $\rho \uparrow$ and $M_J \uparrow$ if $T \uparrow$

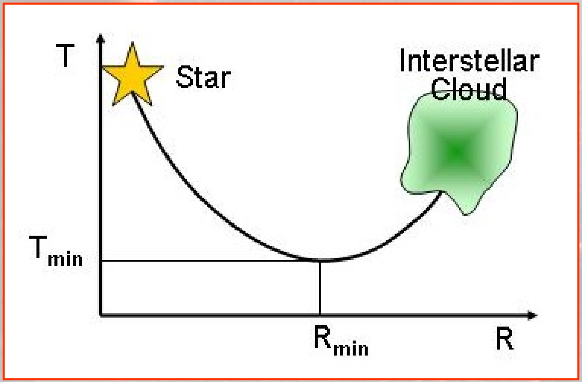
Gravitational Equilibrium

$$\frac{3\mathcal{R}MT}{\mu} = \alpha\frac{GM^2}{R} + 4\pi R^3 P_{\text{ext}}$$

$$\frac{d}{dR}\left(\alpha\frac{GM^2}{R} + 4\pi R^3 P_{\text{ext}}\right) = 0$$

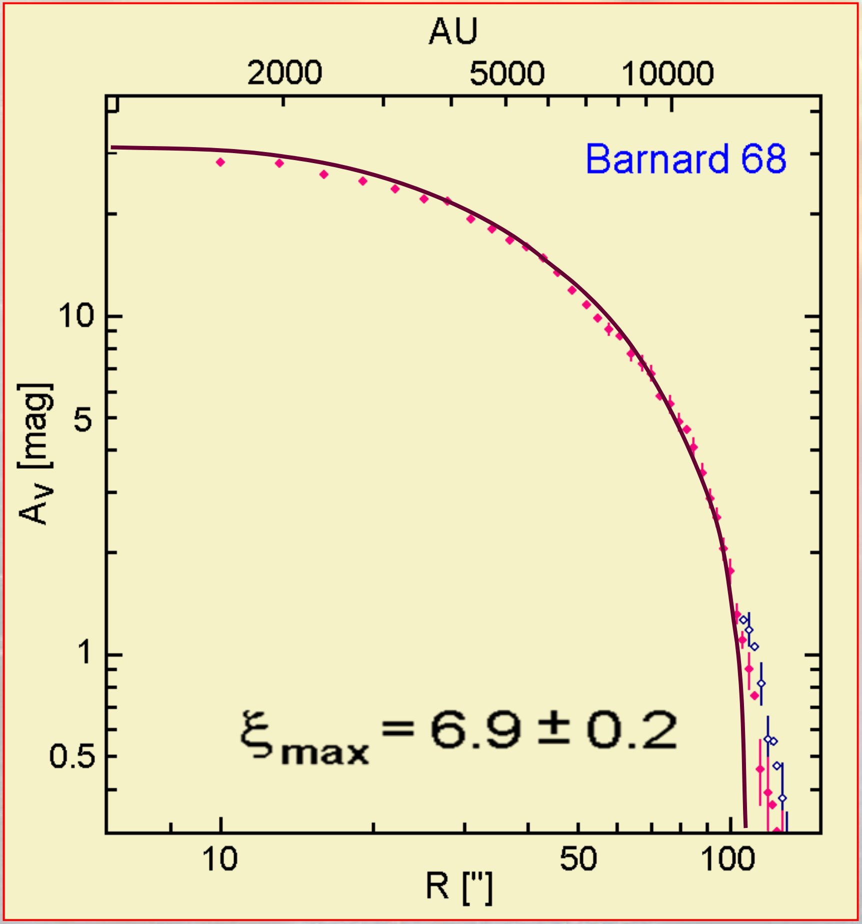
$$-\alpha\frac{GM^2}{R^2} + 12\pi R^2 P_{\text{ext}} = 0$$

$$R_{\text{min}} = \left(\frac{\alpha\, GM^2}{12\pi\, P_{\text{ext}}}\right)^{1/4}$$



- Simplified treatment according to the Virial theorem
- Existence of minimum configuration
- Existence of a minimal Radius R_{min} with a corresponding minimal temperature T_{min} before instability sets in
- R_{min} defines also a typical column density
- No stellar equilibria through sequence of hydrostatic configurations
- External radiation field determines T_{min} through heating by UV- and X-rays
- Important role of dust particles, dark clouds

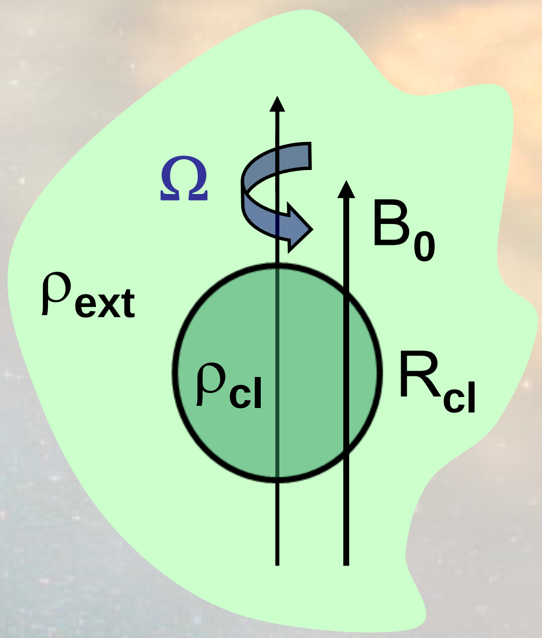
Bonner-Ebert-Spheres



after Alves (2001)

- Isothermal spherical equilibrium, embedded within an external pressure P_{ext}
- Dark cloud: **Barnard 68**
- Fitting by theoretical curve accurately determines the physical properties of the cloud and the ISM pressure
- d = 125 pc
- $M = 2.1\ M_{\odot}$
- R = 12500 AU
- $P_{ext} = 2.5 \cdot 10^{-12}$ Pa

Transport of angular momentum



$$\boxed{\tau_b = \frac{8}{15} \frac{R_{cl}}{v_A} \frac{\rho_{cl}}{\rho_{ext}}}$$

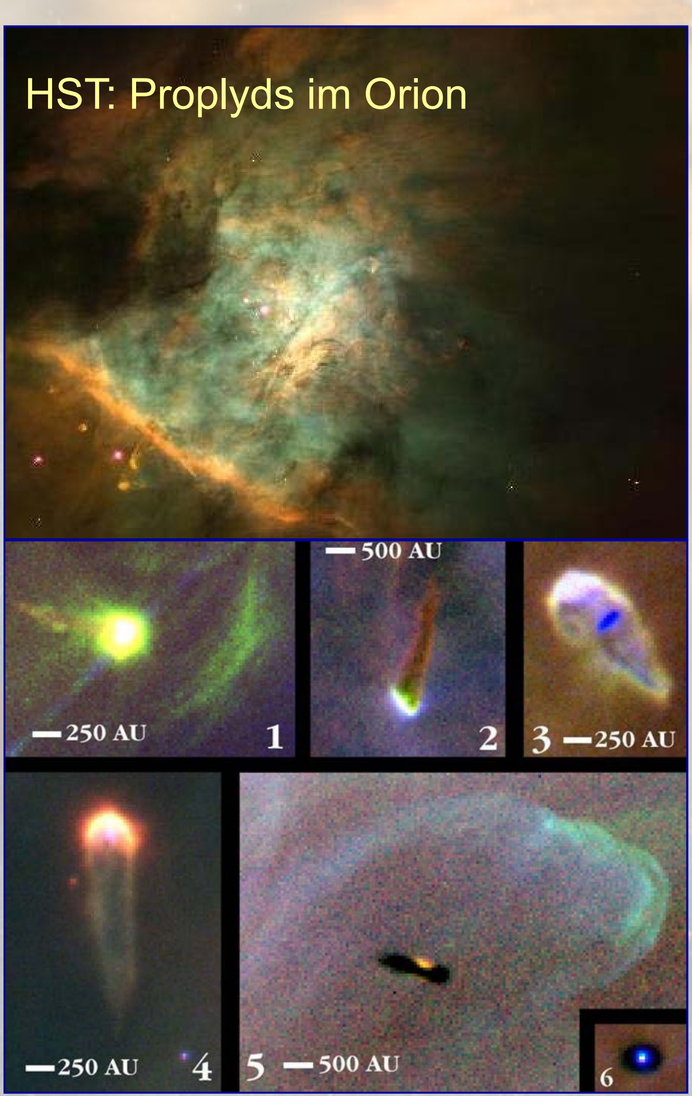
$$\boxed{v_A = \sqrt{\frac{B_0}{4\pi \rho_{ext}}}}$$

- Differential rotation within Milky way induces rotation of interstellar clouds
- **Angular momentum barrier:** Equilibrium between gravity and centrifugal forces
- Specific angular momentum: **ISC/Star=1:10^{-7}**
- **Magnetic braking:** transport of angular momentum by transverse Alfvén-waves in the surrounding medium with v_A
- Braking time scale τ_b: moment of inertia of the cloud is comparable to moment of the accelerated external medium
- **Fragmentation of individual clouds:** Angular momentum redistributed to the angular momentum of individual orbits

Phases of star formation

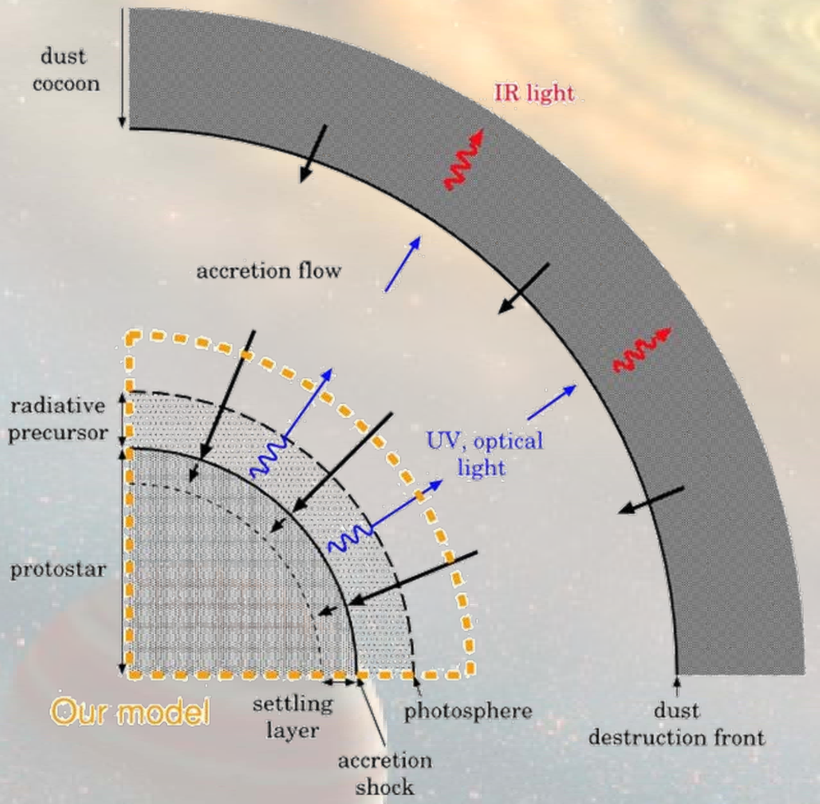
- Interstellar Clouds: Fragmentation necessary since Jeans-mass in interstellar clouds to large
- Transport of angular momentum necessary: specific angular momentum: $J/M_{ISC} \sim 10^{24} cm^2/s$, $J/M_{MS} \sim 10^{17} cm^2/s$
- Stars are formed by a gravitational collapse within Interstellar Clouds, stars are mostly born in clusters
- 1. Phase: Collapse towards a hydrostatic core**, disk formation**
- 2. Phase: Further accretion of mass, material falls supersonically, infall of mater terminated by an almost stationary shock front, luminosity due to accretion , **disk evolution**
- 3. Phase: Quasistatic contraction, Deuterium burning, formation of jets and winds**, disk destruction**

Star forming region



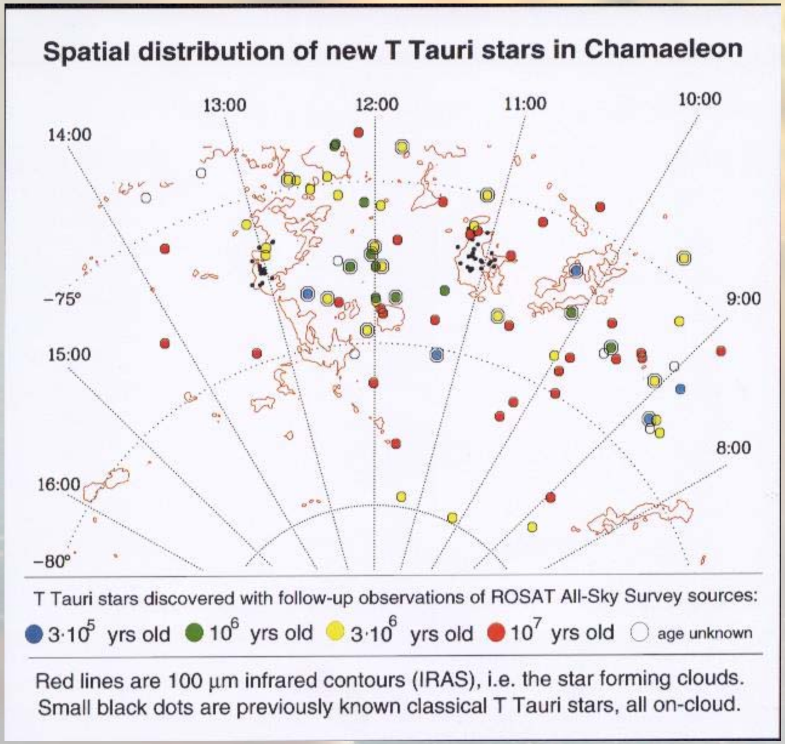
- Orion-nebulae, nearest star forming region in d=480pc
- About 200 young stars with different masses
- High UV-fluxes lead to Photoionisation of the whole cloud
- More than 50% of the young stars show accretion disks and/or IR emission from dusty disks
- Around 500 IR-sources have been detected, free floating brown dwarfs or planets?

Protostar



- Central region in hydrostatic equilibrium
- No thermal equilibrium, i.e. contraction, the potential energy is released partly by radiation, thermal heating
- Accretion of matter, accretion shock front where the kinetic energy is transformed into heat and radiation, melting of dust particles, dissociation of molecules, opacity gap
- High rotation rates, interaction with the surrounding medium, disk formation due to conservation of angular momentum, jets along the rotational axis

T Tauri Associations



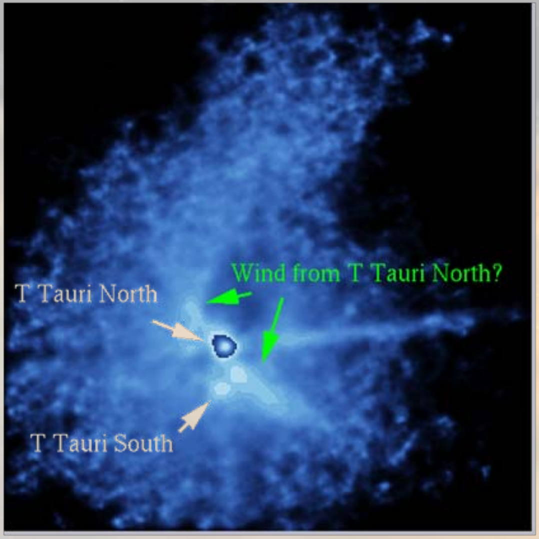
Spatial distribution of new T Tauri stars in Chamaeleon

T Tauri stars discovered with follow-up observations of ROSAT All-Sky Survey sources:

Red lines are 100 µm infrared contours (IRAS), i.e. the star forming clouds. Small black dots are previously known classical T Tauri stars, all on-cloud.

ROSAT/MPE: T Tauri stars

- Stellar clusters of low mass stars
- Interaction with the surrounding medium, high rotation rates, X-ray emission caused by magnetic activity
- Prototype: T Tauri as typical object within a star forming region: Taurus-Auriga
- Observation: Lithium at λ=670,7nm, detected only in young objects
- Circumstellar disks ranging from 10^{-3} to 1 $M_\odot$, dimensions from 10^2 to 10^3 AU



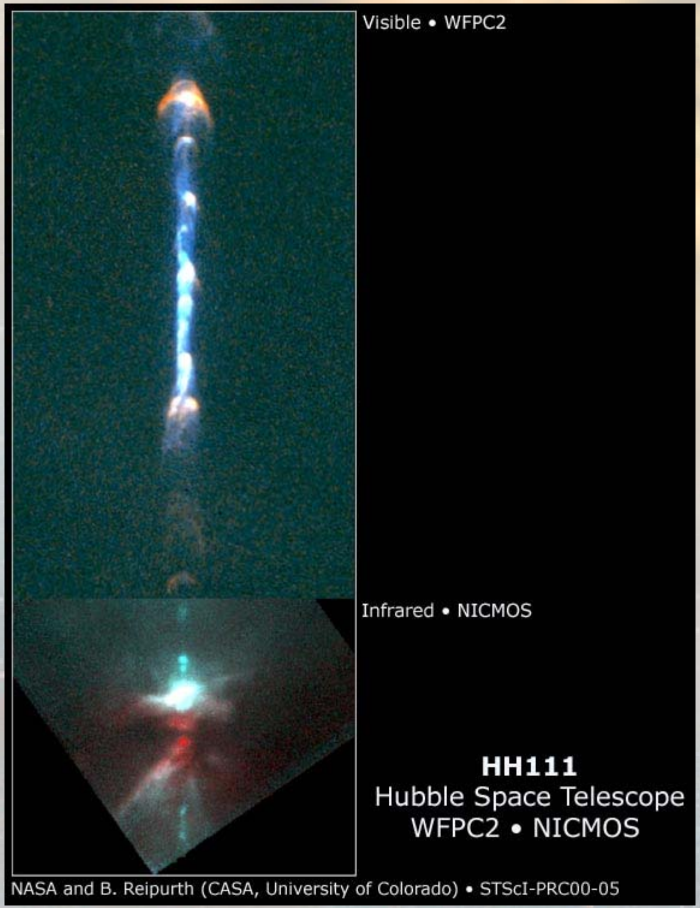
CHFT: T Tauri binary, IR-colours

2MASS; T Tauri + Hind‘s nebulae

T Tauri

- T Tauri: eruptive, variable star in Taurus dark cloud, m_V~9-14^{mag}
- Prototype for a young low mass star, age ≤ 10^7 years, $M \leq 3M_\odot$
- X-ray emission from large flares, magnetic fields generated and amplified through dynamo processes in rapidly rotating stars, v sin i ~ 20km/s (120km/s for centrifugal balance)
- T Tauri at d=141.1±2.8 pc from radio astronomical VLBI-measurements, luminosity L ~$3.7L_\odot$
- T Tauri : close binary, complicated system, showing several interactions and time-dependent mass loss

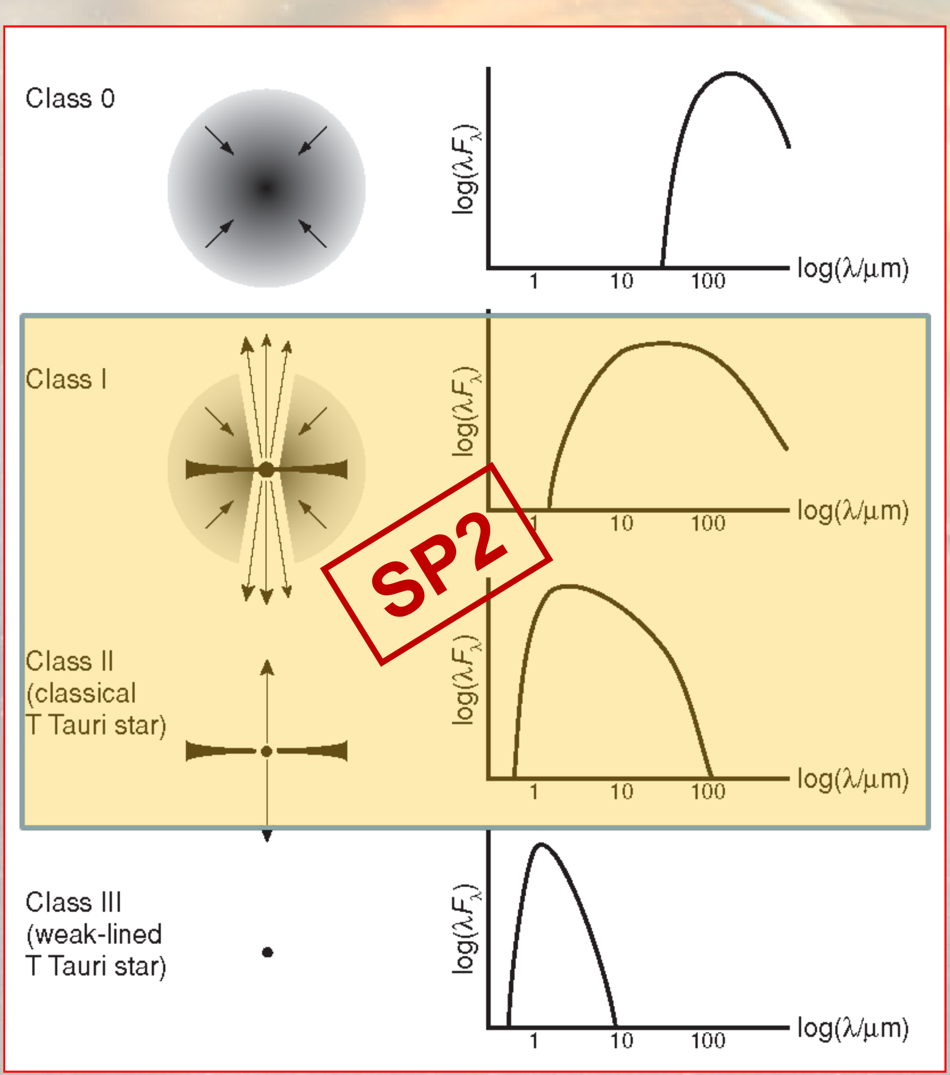
Jets from young stars



NASA and B. Reipurth (CASA, University of Colorado) • STScI-PRC00-05

- Stellar winds and activity observed in young stellar sources, e.g. T Tauri stars
- Jets along the rotational axis, v~100 km/s, focusing through the circumstellar disk
- Most visible is interaction with the ISM
- Emission Spectra of molecules, excited by shock waves
- Working surface at the end of these jets, so-called Herbig-Haro objects
- Interactions with the protoplanetary discs, shaping of the disc surface and irradiation by high energy photons and/or energetic particles

Classification of YSO

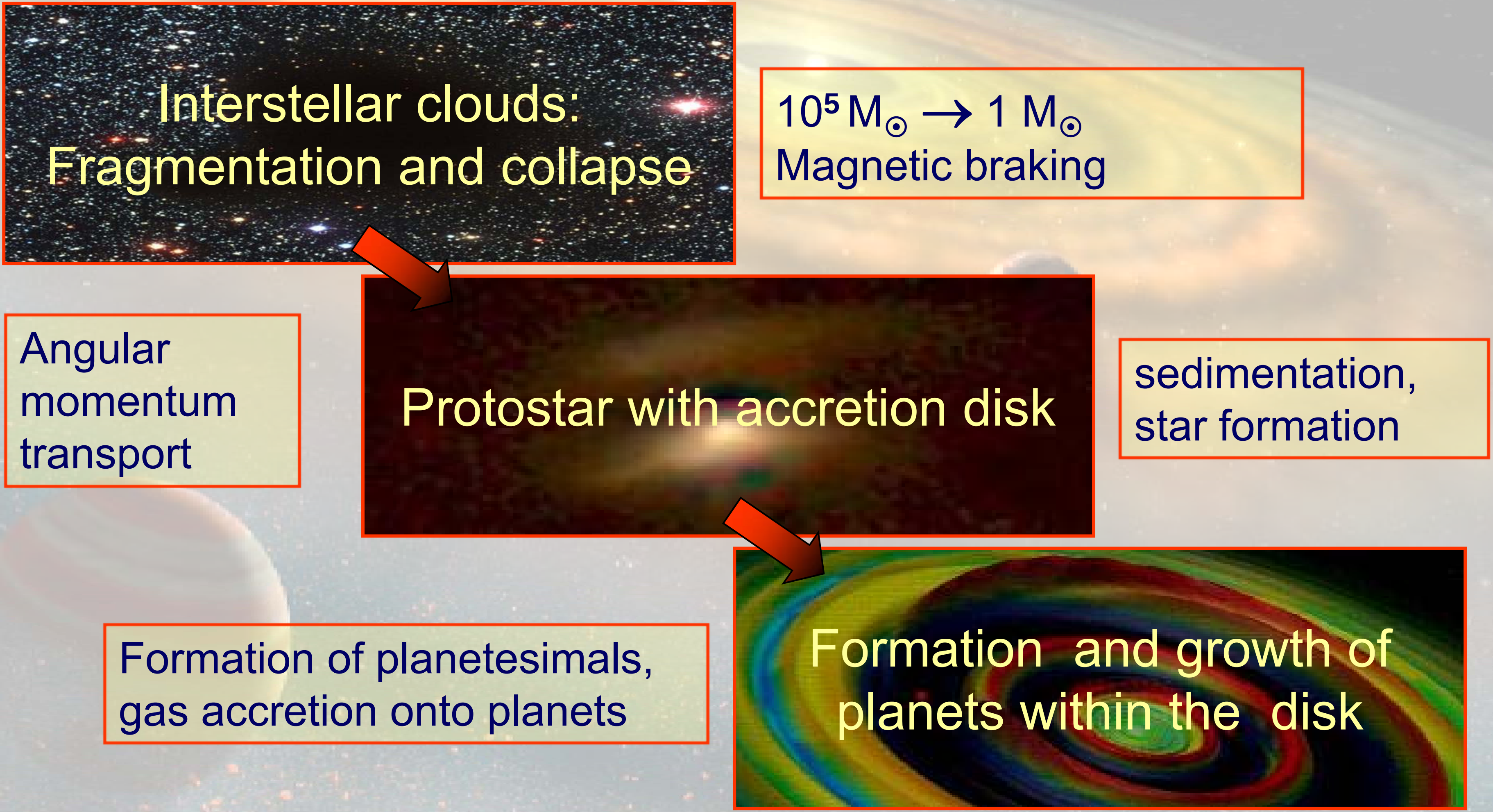


- Young Stellar Objects: Classified depending on slope of the IR-flux measured between 2.2µ (K-band) and mid IR (10 µm or 24 µm)

$$\alpha_{\mathrm{IR}} = \frac{\Delta \log(\lambda F_\lambda)}{\Delta \lambda}$$

- Classification due to observational properties, e.g. Class 0 sources are deeply embedded
- Importance of disk contribution deceases, class 3 located above main sequence at HRD

Schematic formation of planets



Interstellar clouds:
Fragmentation and collapse

$10^5 M_\odot \rightarrow 1 M_\odot$
Magnetic braking

Angular momentum transport

Protostar with accretion disk

sedimentation,
star formation

Formation of planetesimals,
gas accretion onto planets

Formation and growth of planets within the disk

Summary:
Formation of stars and planets

- Stars are formed out of the densest parts of interstellar clouds by a gravitational instability
- Planets form in protostellar accretion disks, no direct collapse from ISM
- Many details still under debate
- Better and more observations needed
- Diversity of planets (mass, distance to central source, eccentricity, chemical abundances, etc.) indicates a large number of processes involved during the formation process

Definition of planets

- Informal definition: large body, orbiting around a star, not massive enough to ignite nuclear fusion
- Upper mass limit: 13 M_J with Jupiter mass M_J=1.899 x10^{30} g, more massive objects are called brown dwarfs
- Lower mass limit necessary to clear orbit (IAU definition)
- Knowledge from our Solar System and from more than 800 extrasolar planets with leak of detailed information, only orbital periods, mass estimates, ...
- Extrasolar planets: growing numbers, statistical properties, observational bias towards larger bodies in close orbits
- Planets are composed of gas, ices and rocks
- Age of Solar System from radioactive dating: 4.56 x10^9 years

Direct imaging of extrasolar planets

- Planet with Radius R_p, orbiting at distance a having an Albedo A reflects

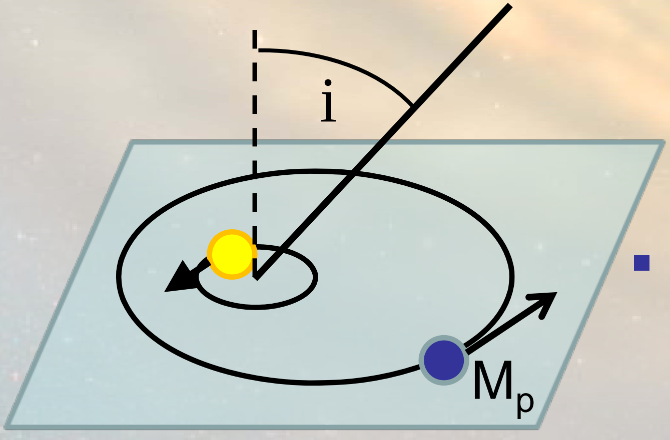
$$f = \left(\frac{\pi R_{\mathrm{p}}^2}{4\pi a^2}\right) A = 1.4 \times 10^{-10} \left(\frac{A}{0.3}\right) \left(\frac{R_{\mathrm{p}}}{R_{\oplus}}\right)^2 \left(\frac{a}{1\ \mathrm{AU}}\right)^{-2}$$

- Approximation of radiation by a back-body with T_p=290K leads to $\lambda \approx 20\mu m$ with $h\nu_{max}=2.8\ k_B T$ and

$$f = \left(\frac{R_{\mathrm{p}}}{R_*}\right)^2 \frac{\exp(\mathrm{h}\nu/\mathrm{k_B} T_*) - 1}{\exp(\mathrm{h}\nu/\mathrm{k_B} T) - 1}$$

- Values for the Earth and our Sun give $f \sim 10^{-6}$ at IR ($\lambda \sim 20\mu m$)
- Earth at 0.5 AU at d=5 pc: θ=0.1" , requires a 50m telescope

Doppler motions of Exos



- Keplerian motion for $M_* \gg M_\mathrm{p}$ at distance a:

$$v_\mathrm{K} = \sqrt{\frac{GM_*}{a}}$$ and $$P = 2\pi\sqrt{\frac{a^3}{GM_*}}$$

- Orbital velocity of the star determined by the center of mass:

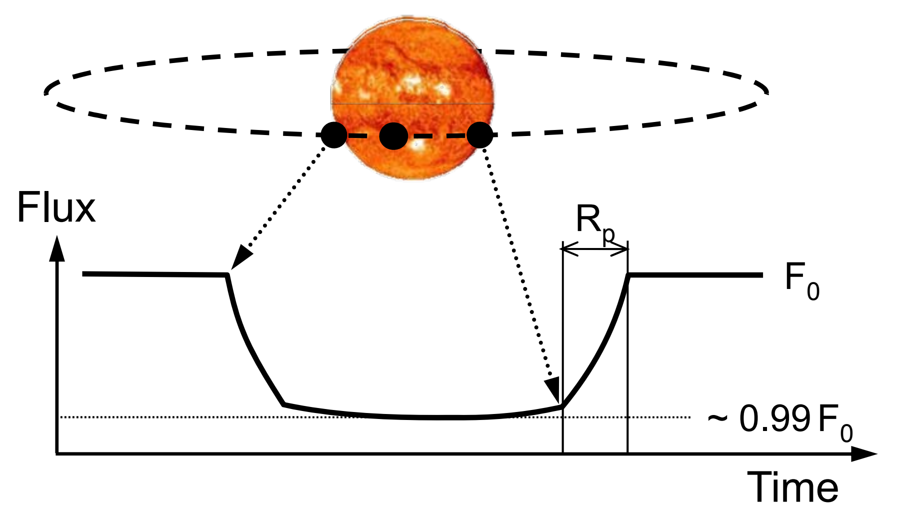
$$M_* v_* = M_\mathrm{p} v_\mathrm{K}$$

- Radial variation varies sinusoidally with a semi-amplitude

$$K = v_* \sin i = \left(\frac{M_\mathrm{p}}{M_*}\right)\sqrt{\frac{GM_*}{a}} \sin i$$

- Lower limit of planet mass via → $M_\mathrm{p} \sin i$

Transients of extrasolar planets



- Decrease of the stellar flux in case of uniform brightness

$$R_\mathrm{p} \simeq R_\mathrm{Jup} \Longrightarrow f \simeq 0.01$$

- Detection of earth-like planets

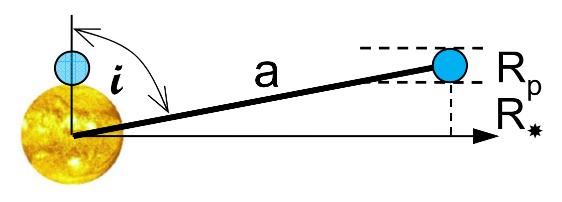
$$f = 8.4 \cdot 10^{-5} \left(\frac{M_\mathrm{p}}{M_\oplus}\right)^{2/3}$$

- Transit times from geometry (e.g. Quirrenbach, 2006)

$$t_\mathrm{transit,\,max} = 2R_*/v_\mathrm{K}$$

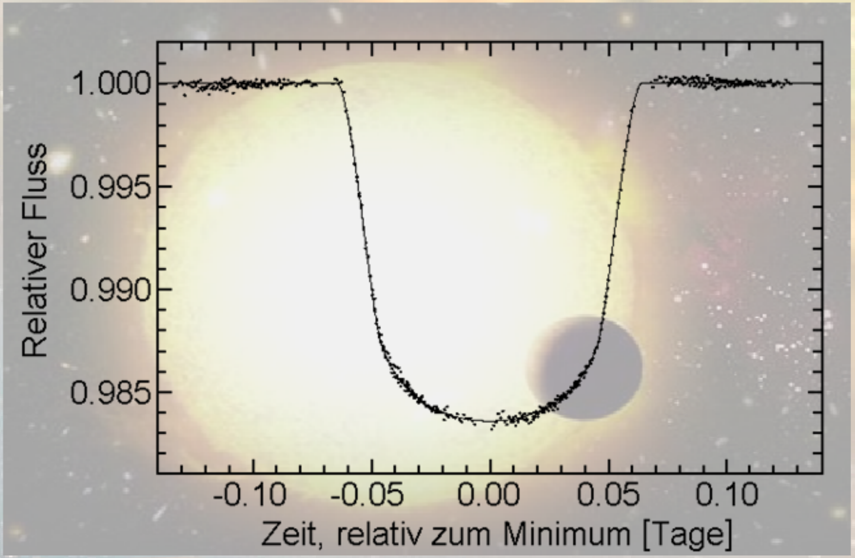
$$f = \left(\frac{R_\mathrm{p}}{R_*}\right)^2$$

$$\cos i \leq \frac{R_\mathrm{p} + R_*}{a}$$



$$t_\mathrm{transit} = \frac{P}{\pi} \sin^{-1}\left(\frac{\sqrt{(R_* + R_\mathrm{p})^2 - a^2\cos^2 i}}{a}\right)$$

Exoplanet around HD 209 458



Brown et al. 2001

- HST-observations allow precise transit photometry, several transits observed
- Star: G0V (Sun: G2V), d=47pc
- Star with $R_* = 1.146 \pm 0.050\ R_\odot$
- Planet with $R_p = 1.347 \pm 0.060\ R_J$
- P = 3.524 days, a = 0.0468 AU
- Inclination: $i = 86.68° \pm 0.14°$
- Possibility to detect earth-like planets

Literature

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