Disks around Young Stellar Objects

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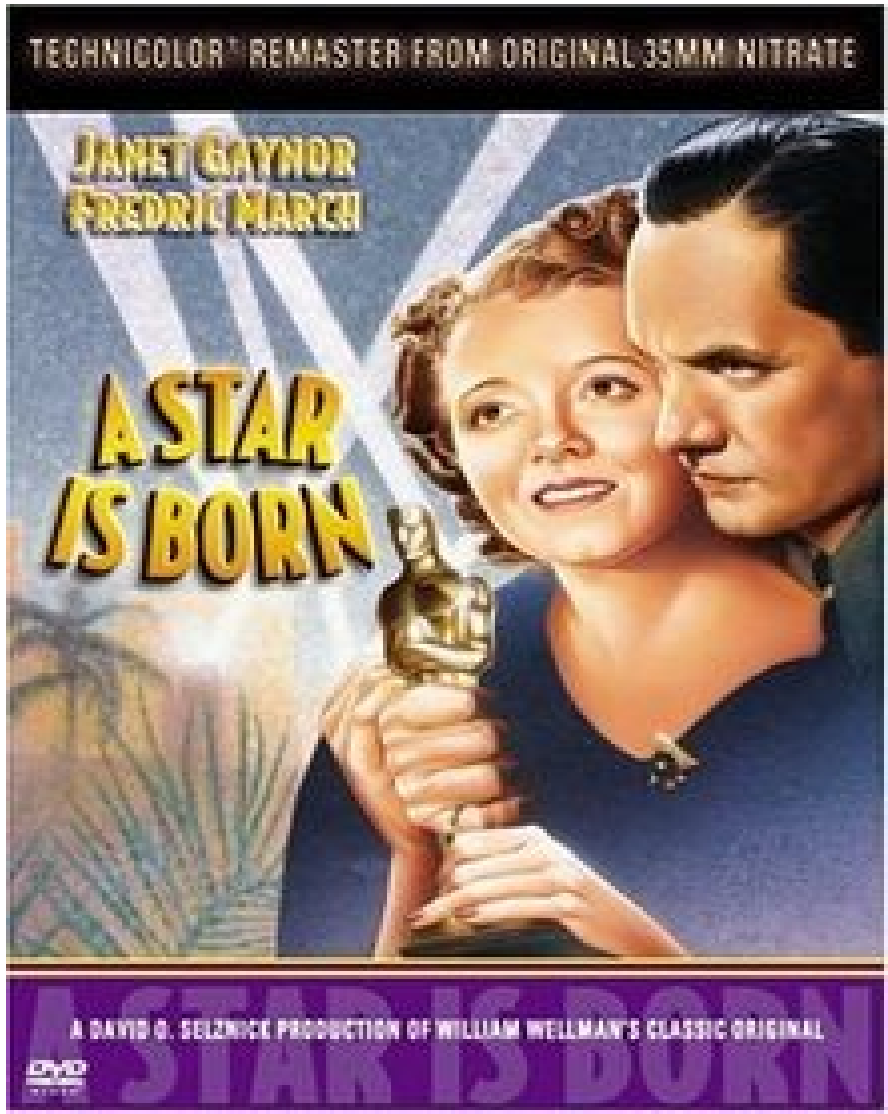
1939

S. Chandrasekhar's classic monograph **(Chandrasekhar, 1939)** on the theory of **"Stellar Structure"** was published in 1939. In it, he restricted his study to stars that are in equilibrium and are in a steady state. Questions regarding the origin of stars and pre-stellar objects and their structure were not considered. In the early 1930s it was still not clear whether star formation is taking place at the present time.

Only by 1938, with the work of Bethe and others on thermonuclear burning of H into He as the energy source for main sequence stars **(Bethe, 1939)**, did it become clear that massive OB stars can not survive for more than a few million years on hydrogen fusion reactions and therefore must have been born recently. The co-existence of lower -mass stars together with OB stars in some star clusters implies that these low mass stars are also of recent birth.

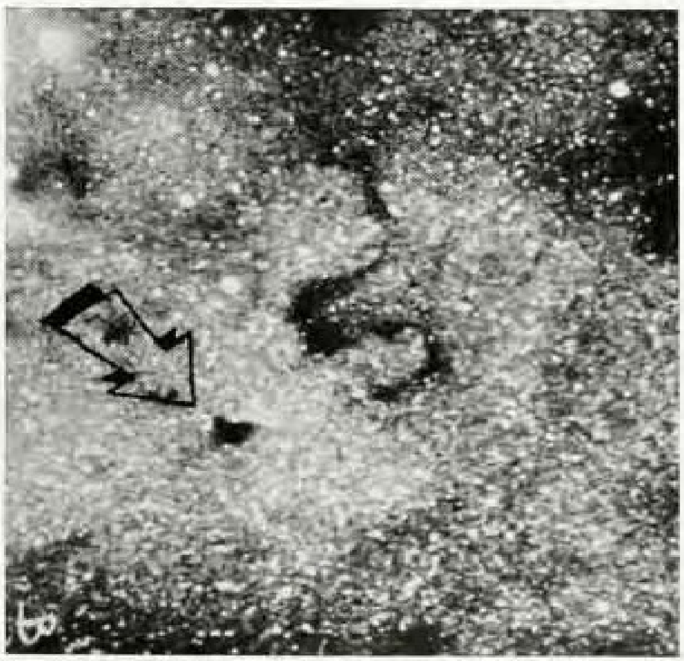
While the need for recent star formation was fully acknowledged, no one had yet recognized an object that could be called a star in the process of being born

Where are the stars born?



A Star Is Born (1937 film)

Where are the stars born? *The interstellar medium (ISM) is the only large enough reservoir of material required for current star formation*. Whipple (1946) and Spitzer (1948) first suggested that dust grains in the ISM could be compressed into denser clouds by interstellar radiation, which could then collapse under gravity to form protostars *and stars. Therefore, one may expect to find protostellar and young stellar objects in and around interstellar clouds like the dark globules* (Bok and Reilly, 1947).



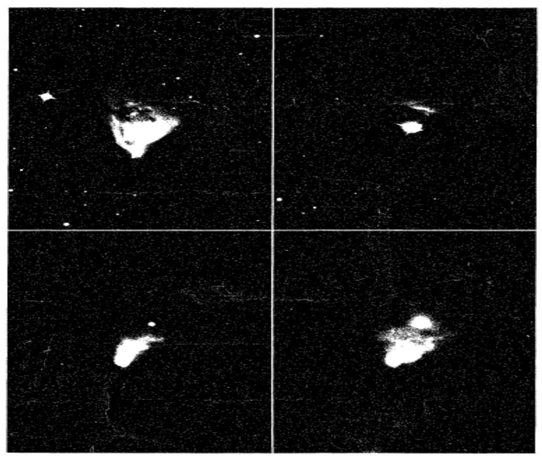
The compact opaque globule may be a protostar, contracting to form a new star.

(L. Spitzer, 1948, *Physics Today* 1, 6)

Candidate young stars discovered

The emission-line variables like T Tauri, discovered by Joy (1942,1945), associated with dark clouds of Taurus, Auriga and other regions of the Milky Way, were recognized as young stars in expanding stellar associations by Ambartsumian (1947). Expanding stellar associations are also the birth sites of massive stars was suggested by Ambartsumian(1947) and Blauuw (1952). Emission-line stars of type Ae/Be, associated with nebulosity in regions of dark clouds, were identified later by Herbig (1960), as young, more massive counterparts of T Tauri stars.

PLATE X



PHOTOGRAPHS OF VARIABLE STARS WITH ASSOCIATED VARIABLE NEBULAE

R Mon with NGC 2261 (*upper left*), 1920 January 26, photographed by E. Hubble; T Tau with NGC 1555 (*upper right*), 1940 September 30, photographed by W. Baade; R CrA with NGC 6729 (*lower left*), 1920 August 15, and (*lower right*), 1941 August 17, photographed by E. Hubble. 100-inch reflector.

R Mon, T Tauri and R CrA (Joy, A.H., 1945, ApJ, 102, 168)

Predicted characteristics of pre-main-sequence stars:_

Proto-stellar and young pre-main-sequence stellar objects in the process of formation from dense interstellar clouds by contraction under gravity were predicted to have the following characteristics.

i) Colder, larger, above the main-sequence

Theoretical work by Salpeter (1954) on the reactions of light nuclei (D, Li, Be, B) in young contracting stars and stellar evolutionary tracks for such objects by Henyey et. al. (1955) predicted that they would occupy positions to the right (lower temperature) and above (higher luminosity) the main-sequence in the Hertzsprung-Russell (HR) diagram. This was confirmed by Walker (1956) for lower mass stars, including the T Tauri variables, in the young cluster NGC 2264, from a photoelectric colour-magnitude diagram.

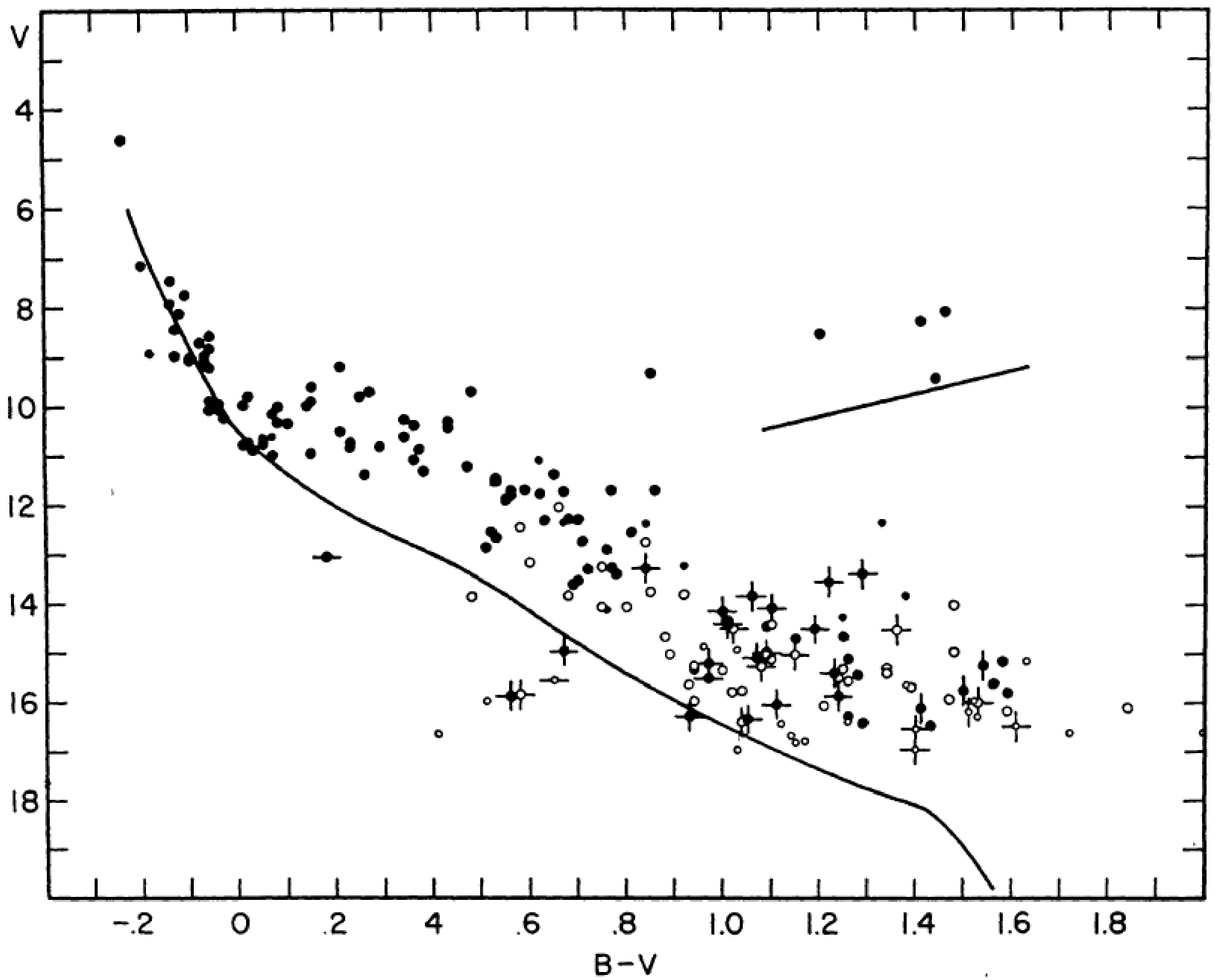


FIG. 4.—Color-magnitude diagram of NGC 2264. Dots represent photoelectric, and circles photographic, observations. Vertical lines indicate known light-variables; horizontal lines indicate stars having bright Hα. Small symbols indicate observations of lower weight. Observed values of the magnitudes and colors have been plotted. The lines represent the standard main sequence and giant branch of Johnson and Morgan (1953), corrected for the uniform reddening of the cluster.

(M.F. Walker, 1956, ApJS, 2, 365)

ii) Infrared excesses due to the circumstellar matter

Observations of T Tauri stars and related objects like R Mon at infrared wavelengths up to 5 μ (Mendoza, 1966) and 20 μ (Low and Smith, 1966) showed a large flux excess above that expected from a stellar photosphere. The infrared excess was interpreted (Low and Smith 1966; Davidson and Harwit 1967) as emission from protostellar cloud dust that still surrounds the central young stellar object (YSO); as it absorbs light from the central YSO, gets heated and re-radiates at longer wavelengths.

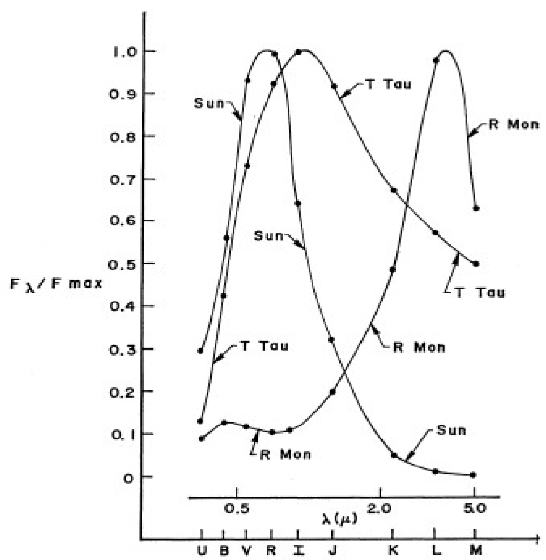


Fig. 1.—The spectral energy-curves for the Sun, T Tau, and R Mon. T Tau illuminates NGC 1555 (Hind's nebula). R Mon illuminates NGC 2261 (Hubble's nebula) (see Herbig 1960, 1962).

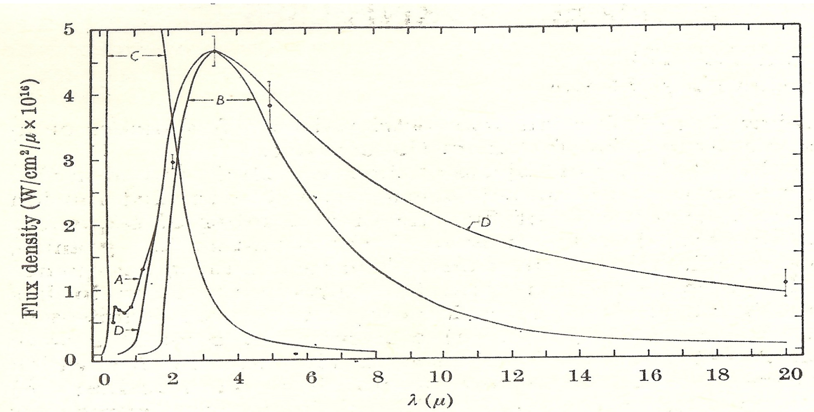


Fig. 1. The absolute spectral energy distribution. Curve *A* is drawn through the U.B.V.R.I.J. observations. The long wavelength observations are shown with their error bars. Curve *B* is an 850° K Planck distribution fitted to the peak. Curve *C* represents part of a distribution for a solar type star normalized to the same total intensity as *R* Monocerotis; the peak flux of 110×10^{-16} W/cm²/μ occurs at 0·43μ. Curve *D* represents the dust model normalized to the observation at 3·4μ.

(Mendoza, 1966)

(Low and Smith, 1966)

Dust must be in a flattened disk

If the circumstellar dust were spherically distributed around the central YSO, then the mass of dust required to produce the observed infrared fluxes would lead to very large extinction along the line of sight to the central YSO at optical wavelengths, which is generally not observed. Therefore the infrared emitting dust must be distributed in a flattened disk-like geometry (Strom et al. 1972 ApJ 173, 353) and it should also cause polarization when viewed more nearly edge-on due to departure from spherical symmetry. Intrinsic polarization was detected in several pre-main-sequence stars in NGC 2264 by Breger and Dyck (1972).

Thus the nature of the observed infrared excess emission and the intrinsic polarization of the pre-main-sequence stars strongly indicated the presence of circumstellar disks around these YSOs. Disk formation had indeed been expected as a rotating proto-stellar cloud contracts under gravity. For a cloud with initial rotation, conservation of angular momentum prevents contraction of the body as a whole. The cloud is flattened and a disk is formed (von Weizsacker, C.F. 1951, ApJ 114, 165).

The Solar Nebula

A flattened protoplanetary disk had been a part of the Solar Nebula models, first proposed and developed by Emanuel Swedenborg (1734), Immanuel Kant (1755) and 1796 by Pierre-Simon Laplace (1796) in the 18th century.

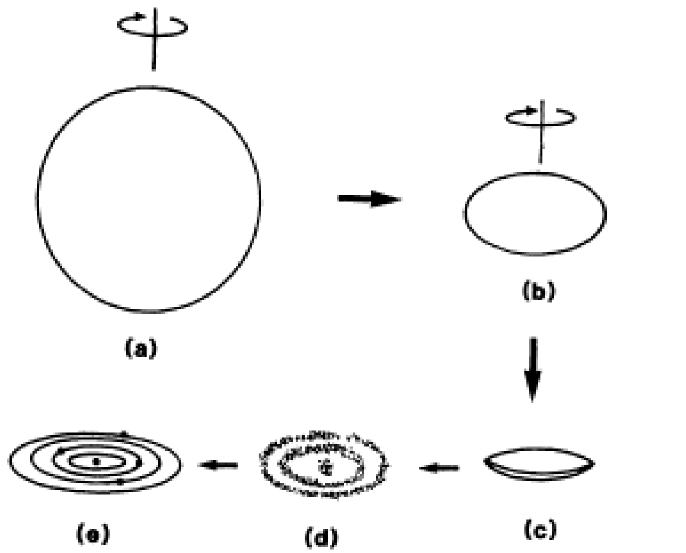
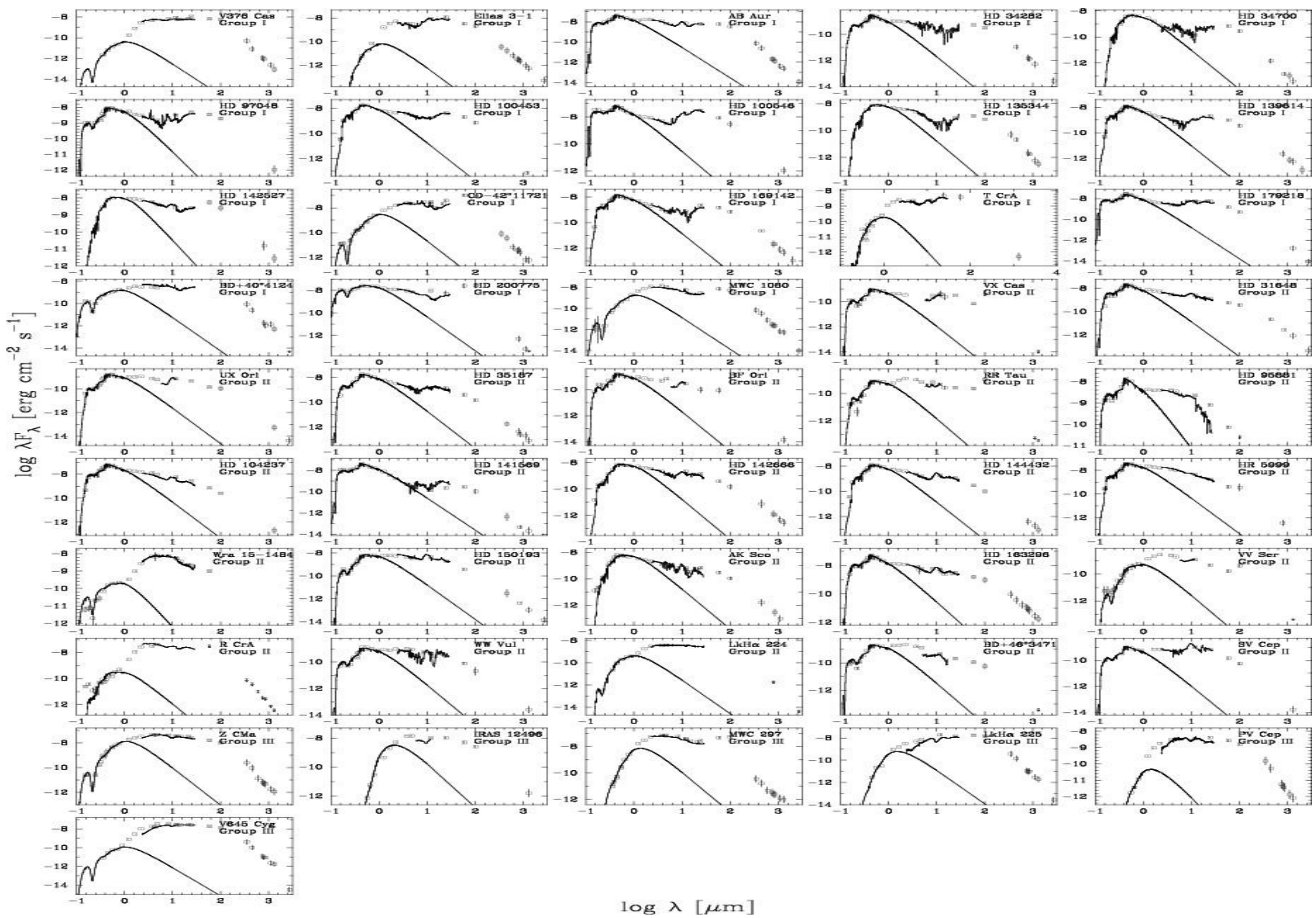


FIG. 1. The Laplace nebula model: (a) a rotating nebula; (b) the collapsing nebula flattened along its rotation axis; (c) formation of a lenticular shape; (d) a series of rings left behind by the contracting core; (e) one residual condensation in each ring forms a planet.

The circumstantial evidence for circumstellar disks

Till around early 1980s, the evidence for the existence of circumstellar disks around YSOs had been indirect, based on the interpretation of optical-infrared spectral energy distributions (SED) and observations of intrinsic polarization of pre-main-sequence stars.

Such studies of SEDs, now extending to far-infrared, sub-millimeter, millimeter and radio wavelengths (eg. Strom, K. M. etal 1989; Beckwith, S.V.W etal. 1990; Evans, N.J. etal 2003; B. Acke, M.E. Van den Ancker; 2004) and polarization (eg. Bastien, P. 1985; Bhatt, H.C. 1996; Bhatt, H.C., Manoj, P. 2004) of a large number of YSOs have shown that they are commonly surrounded by discs with a great diversity in their properties.



The spectral energy distributions of Herbig Ae/Be stars

(B. Acke, M.E. Van den Ancker; 2004, A&A 426, 151)

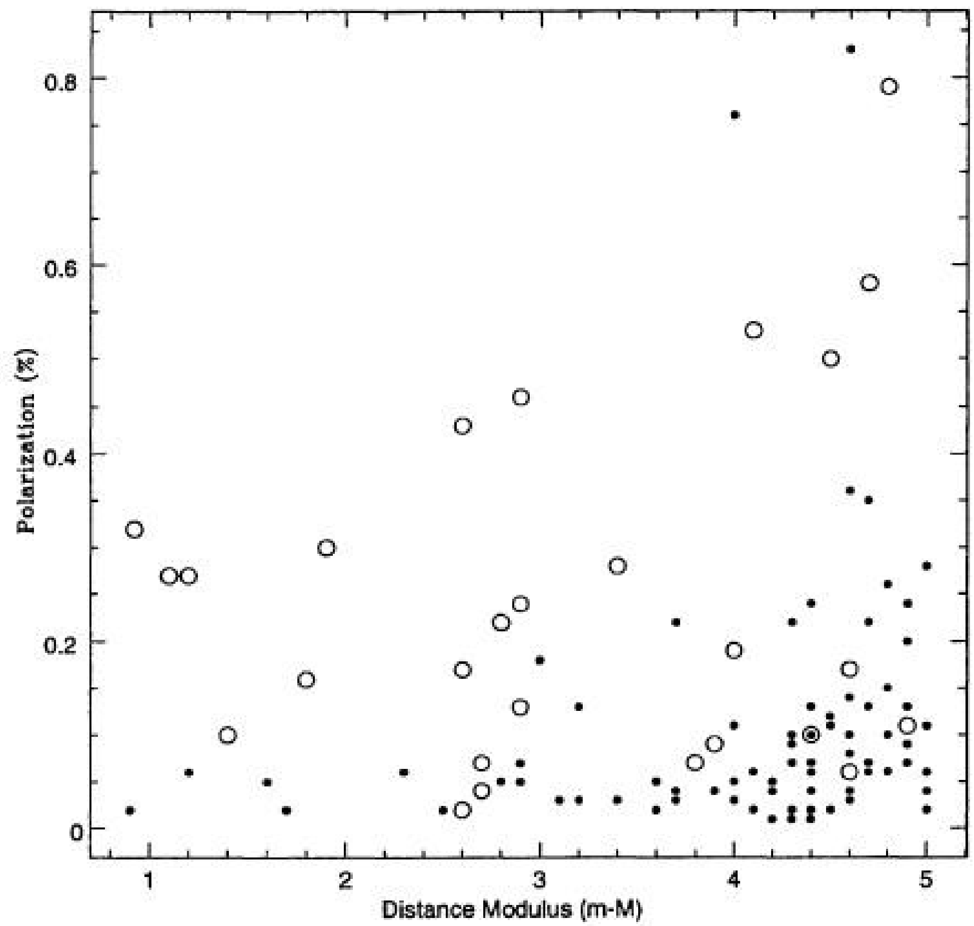


Fig. 1. Plot of degree of polarisation against the distance modulus for the A-type shell stars and anomalous infrared emitters (○) and the general population of A-type stars (•)

Polarization **(Bhatt, H. C. 1996, A&AS, 120, 451)**

Direct evidence for disks : Imaging

The first direct optical image of a circumstellar disc was obtained in **1984** (Smith and Terrile 1984) by "coronagraphic imaging" of the young (about 10 MYr) main-sequence star Beta Pictoris. The disc around Beta Pictoris is seen nearly edge-on and extends to about 500 AU from the star. A circumstellar disc around a very young (10^5 Yr) pre-main-sequence star, HL Tau, was imaged in the near-infrared (1-3 mu) with an infrared camera in 1988 by Monin etal. (1989).

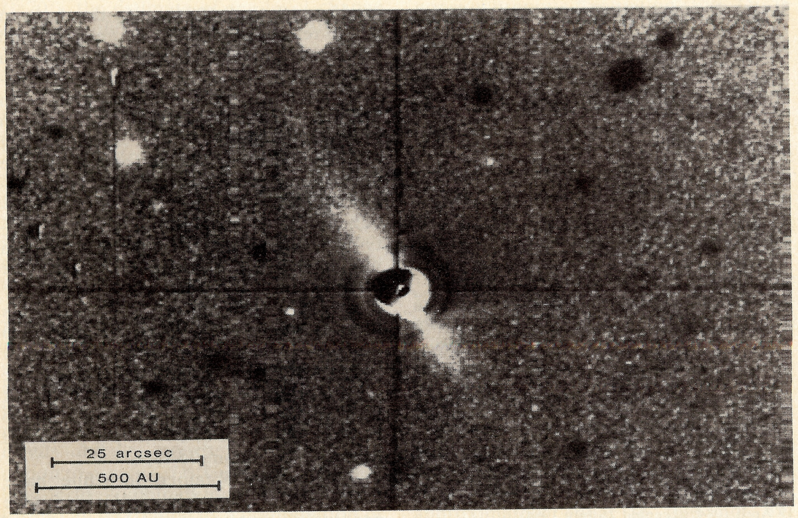
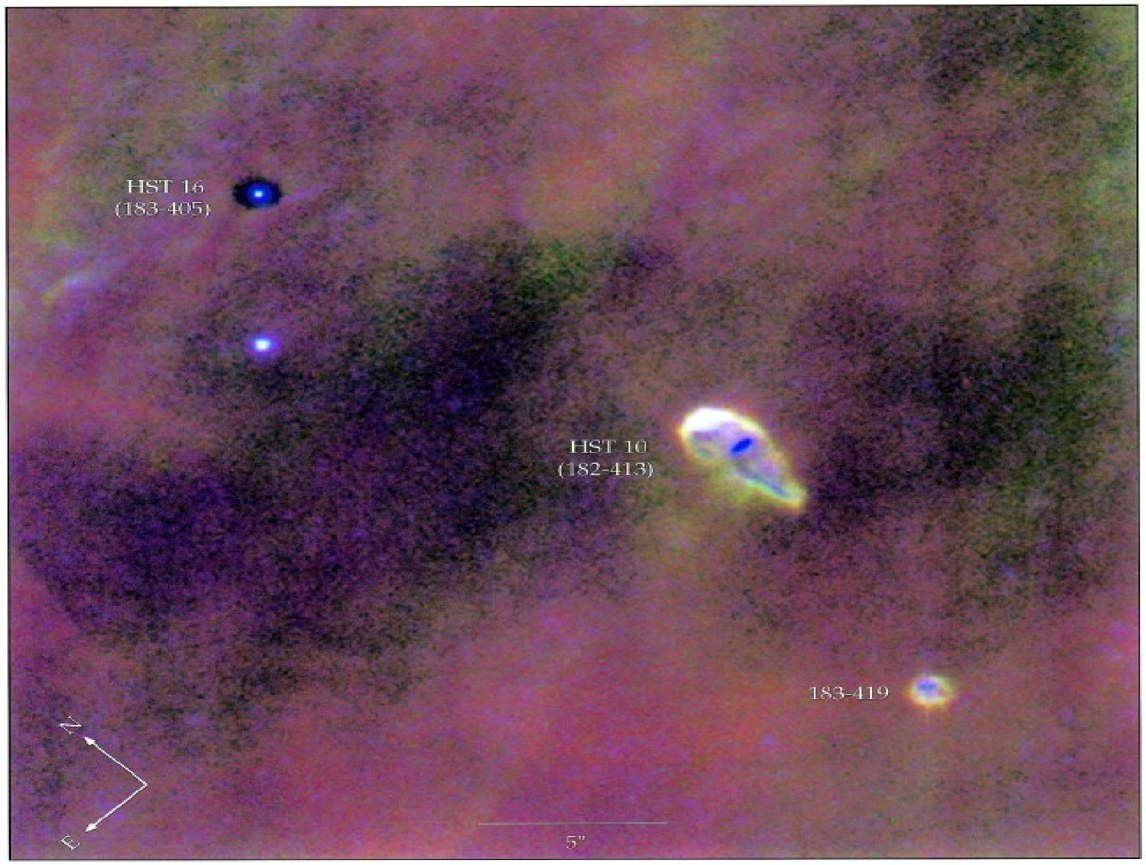


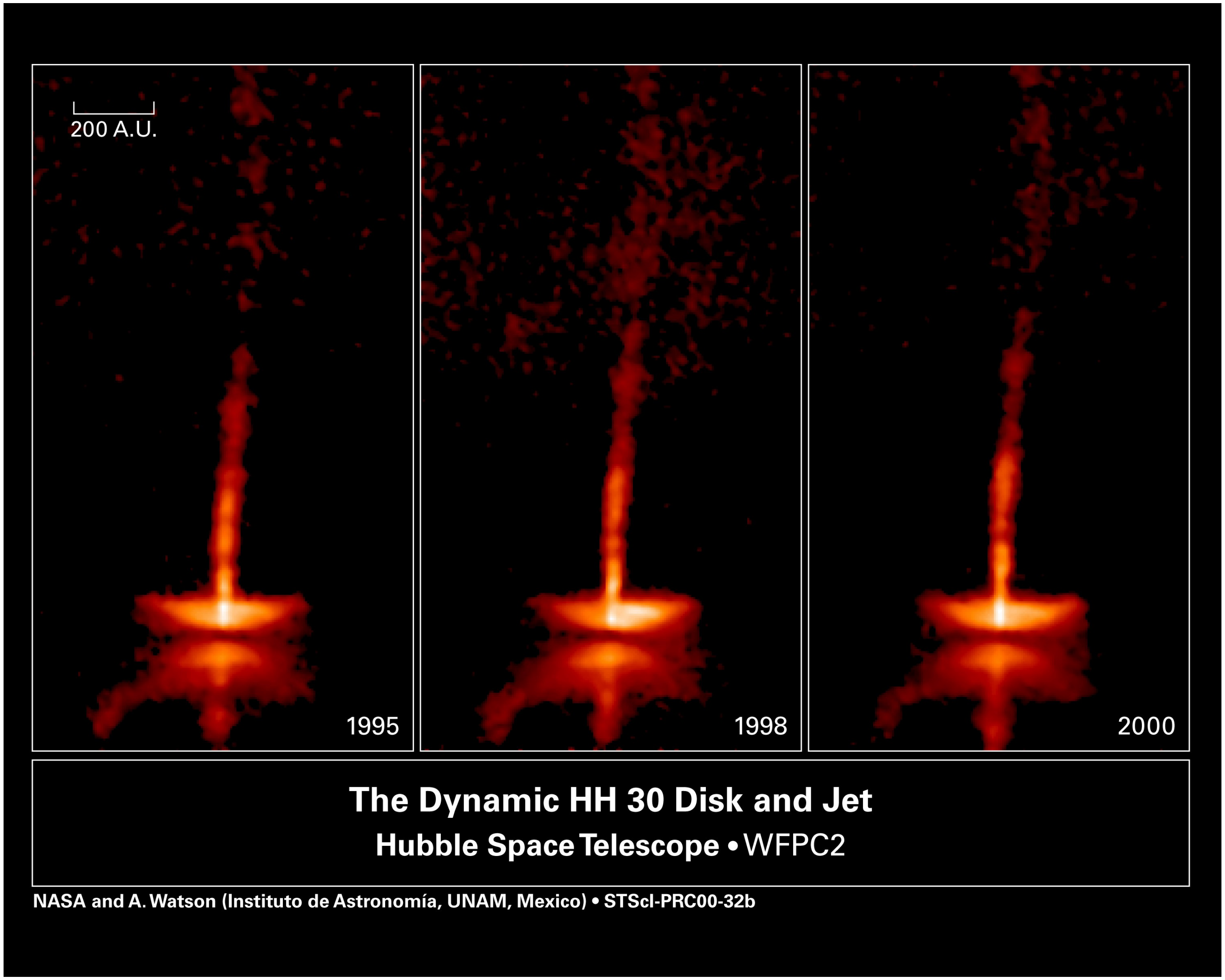
Fig. 1. Ratio image (β Pictoris divided by α Pictoris) showing the edge-on circumstellar disk extending 25 arcsec (400 AU) to the northeast and southwest of the star, which is situated behind an obscuring mask. North is at the top. The dark halo surrounding the mask is caused by imperfect balance in the ratioing process. For further explanation, see text.

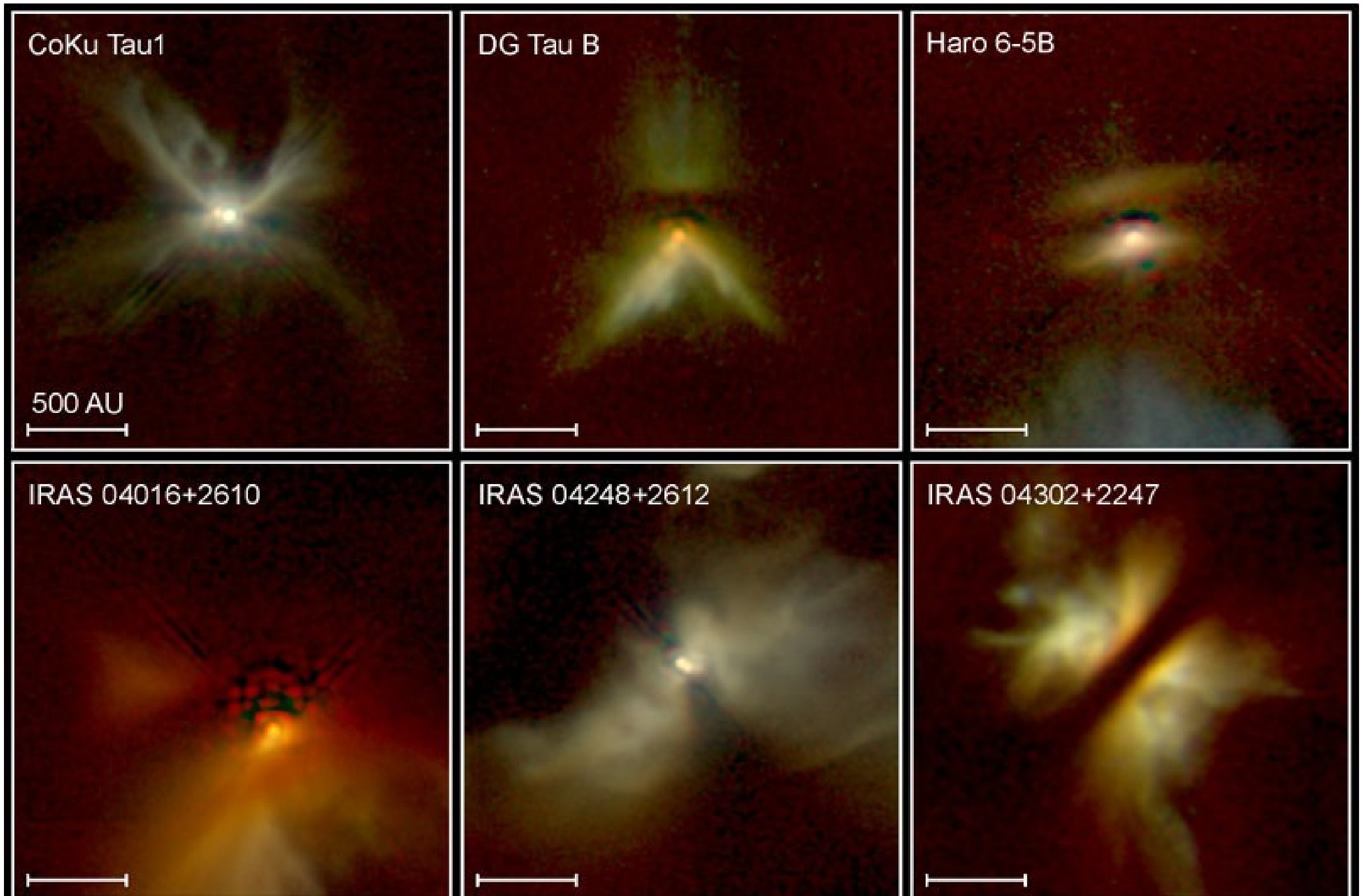
Beta Pictoris disk **(Smith, B.A. and Terrile, R.J., 1984, Science, 226, 1421)**

Since then high-resolution optical imaging with HST, near-infrared adaptive optics on large ground-based telescopes, mm and radio-wave interferometry have been used to image disks around a large number of YSOs revealing disk structure with ever-increasing detail and variety.



Proplyds in Orion: **(O'Dell, C. R., & Wen, Z. 1994, ApJ, 436, 194)**

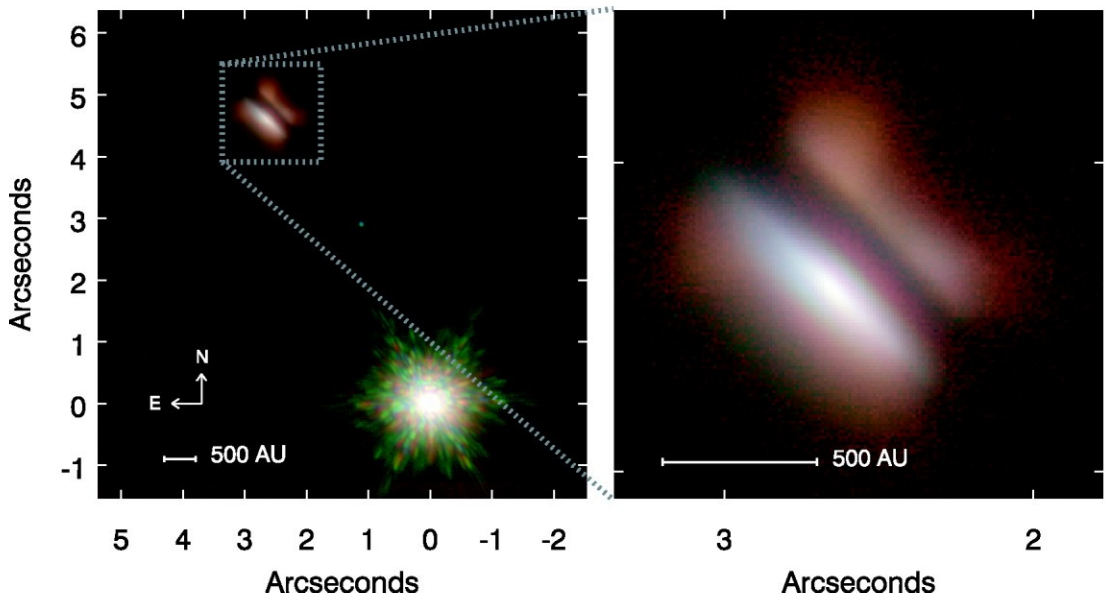

200 A.U.
1995
1998
2000
The Dynamic HH 30 Disk and Jet
Hubble Space Telescope • WFPC2
NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b



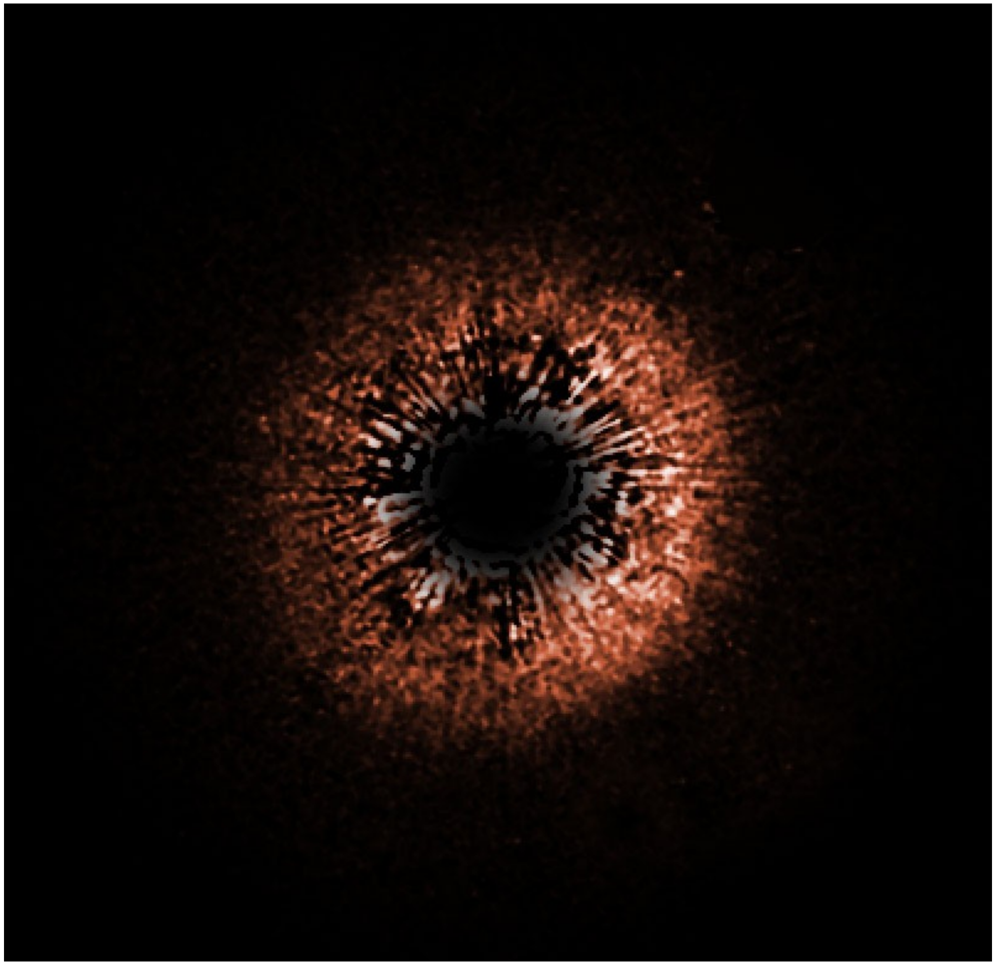
Young Stellar Disks in Infrared **HST • NICMOS**

PRC99-05a • STScI OPO

D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA



Keck AO imaging of PDS 144 (N and S both A type stars) in H, K′, and L bands (Marshall D. Perrin etal. Astrophysical Journal, 645:1272-1282, 2006)



HST image of the face-on debris disk in the G2 dwarf, HD 107146
(Ardila, D. R.; et al. 2004, Astrophys.Journal 617, L147–L150)

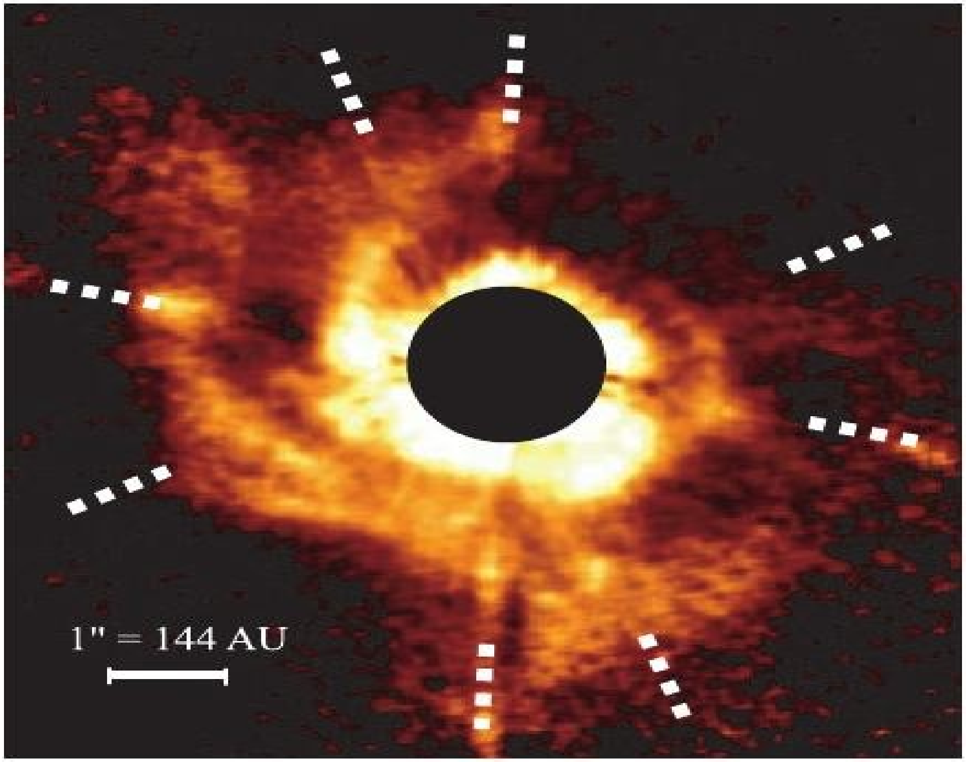


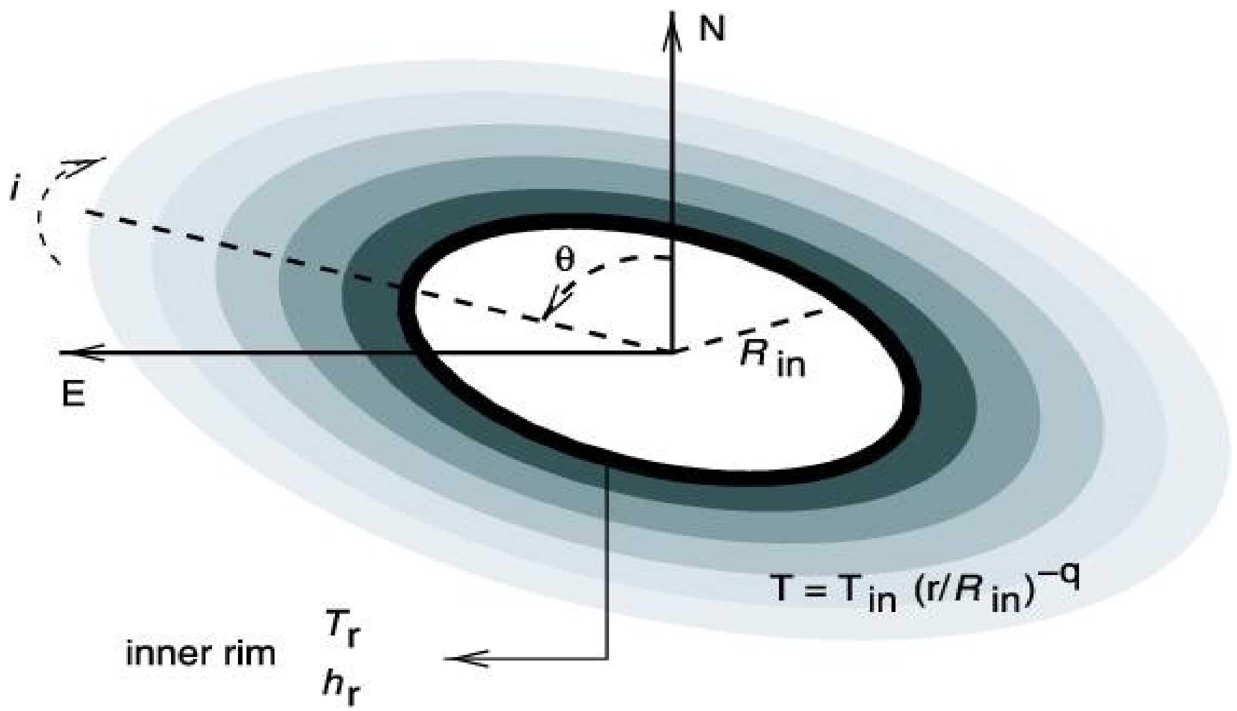
FIG. 1.—*H*-band image of the circumstellar structure around AB Aur after a reference PSF was subtracted. The surface brightness is multiplied by the distance squared from the center for display so that the fainter outskirts can be viewed with a high contrast. Boxcar smoothing is applied with 5 × 5 pixels. Directions of the spider patterns are indicated by dashed lines. The inner area of 1.″7 diameter ($r < 120$ AU; *filled circle*) is photometrically unusable and is masked. The field of view is 8″ × 8″. North is up, and east is to the left.

AB Aur disk : (Fukagawa, M. etal., 2004, ApjL 605, L53)

Disk Models and Structure

a) Thin disks (Active, Passive)

The Spectral Energy Distribution (SED)



$L_\nu = 4\pi D^2 \nu F_\nu$, where F_ν is flux density at distance D from the source. If the disk has inner and outer radii r_0 and R_d, respectively, and is inclined by angle θ to the line of sight ($\theta = 0$ is face on), then

$$L_\nu = 4\pi \cos\theta \int_{r_0}^{R_\mathrm{d}} \nu B_\nu(T)(1 - e^{-\tau_\nu}) 2\pi r dr.$$

B_ν is the usual Planck function, and the optical depth τ_ν

$$\tau_\nu(r) = \kappa_\nu \Sigma(r)/\cos\theta.$$

$\kappa_\nu \propto \nu^\beta$.

is opacity

If $\tau_\nu \ll 1$:

$$F_\nu \propto \kappa_\nu \times B_\nu(T_d) \times M_d$$

If $\tau_\nu \gg 1$:

$$F_\nu \propto B_\nu(T_d) \times Area$$

Temperature and surface density distributions:

$$T(r) = T_0(r/r_0)^{-q},$$
$$\Sigma(r) = \Sigma_0(r/r_0)^{-p}.$$

For a flat disk accreting at a steady rate M. , surrounding a star of mass *M* and radius *R**

$$T(r)^4 = \frac{3GM\dot{M}}{8\pi\sigma r^3}\left[1 - \sqrt{R_\star/r}\right],$$

which for large radii tends to $T(r) \propto r^{-3/4}$

(D. Lynden-Bell and J. Pringle, *MNRAS* 168 (1974), p. 603)

For a passive reprocessing disk

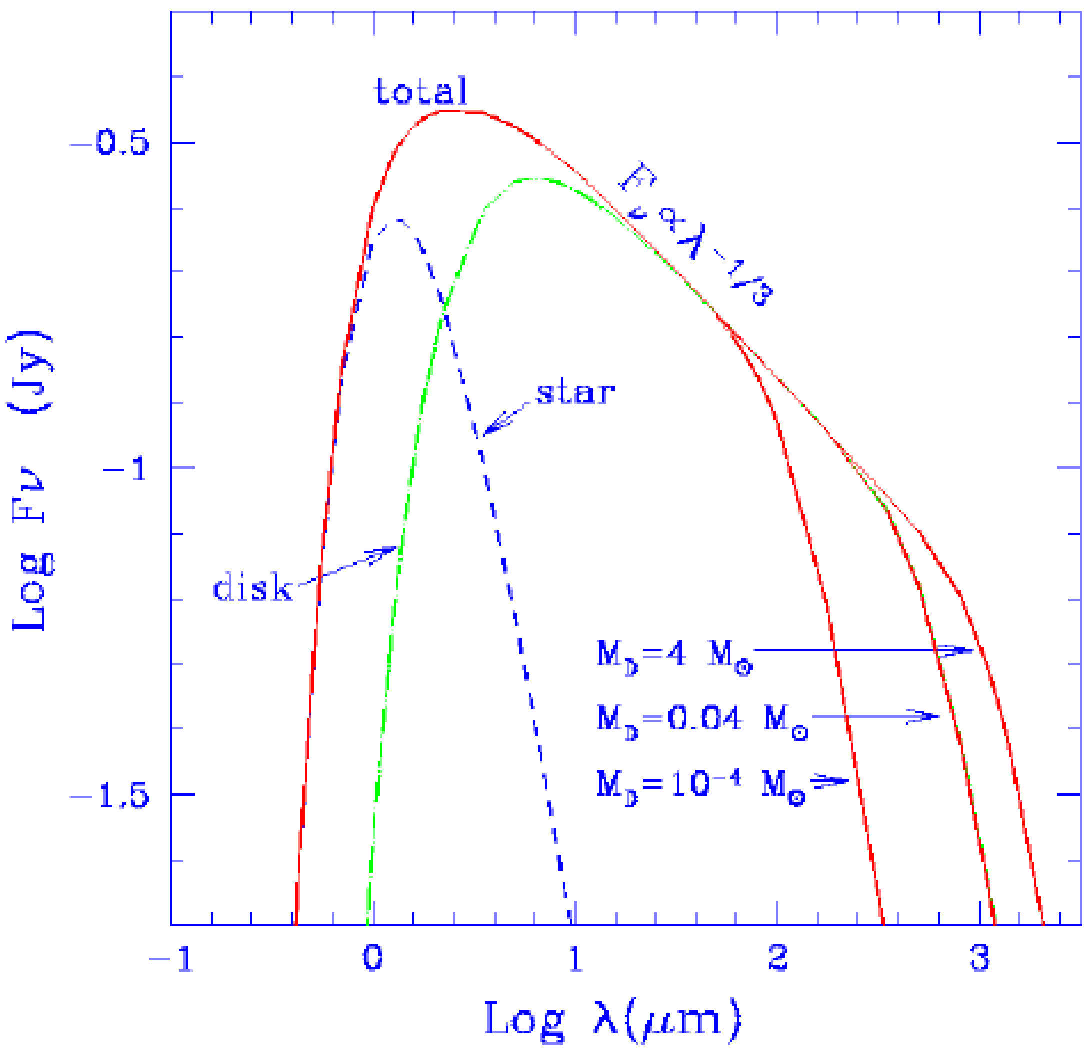
T(r)^4 = T*^4[sin^−1 (R* /r) − (R* /r)SQRT(1 − (R* /r)^2] /π

Again $T(r) \propto r^{-3/4}$ at large radii.

(F. Adams and F. Shu, *ApJ* 308 (1986), p. 836)

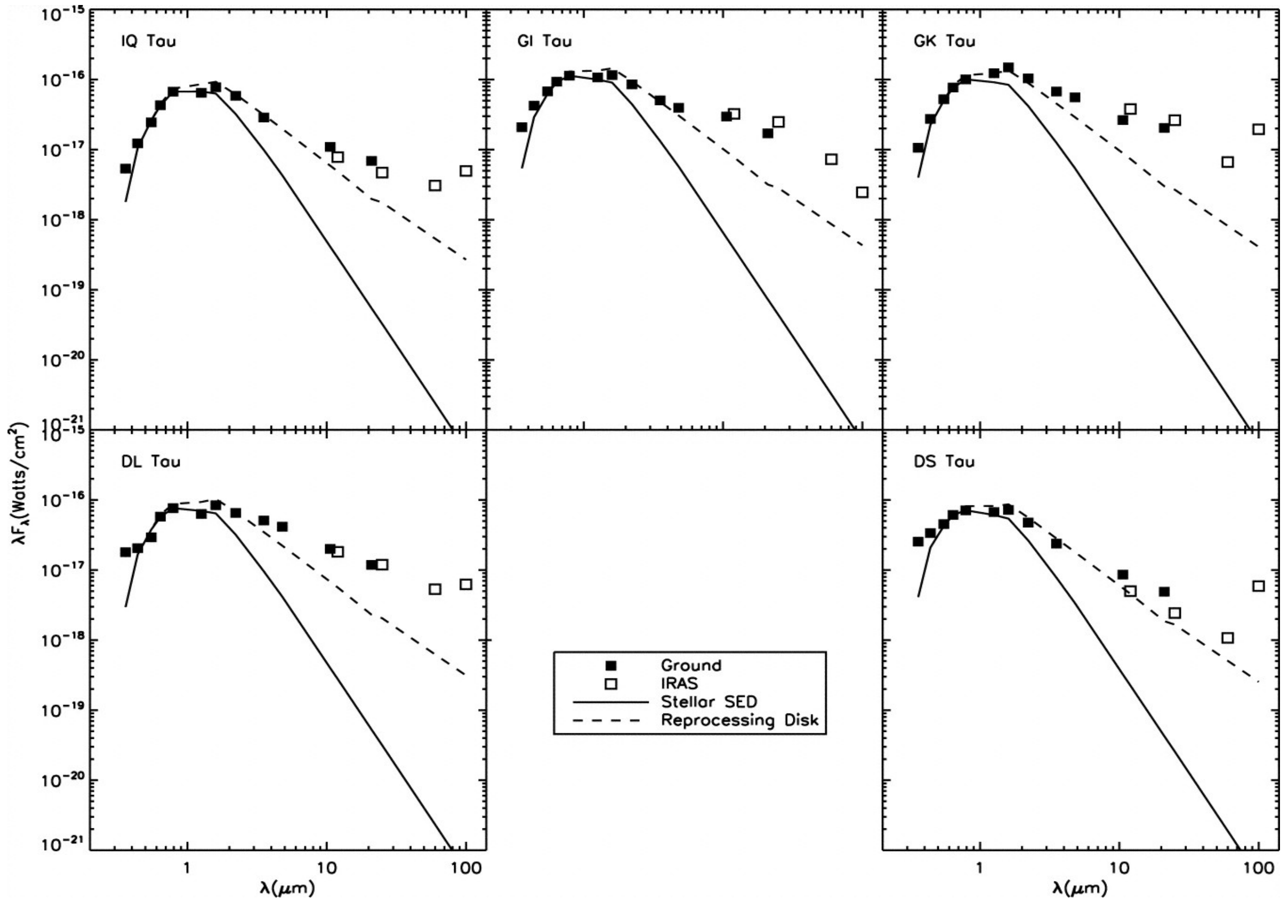
The SED for such thin disks

for small frequency ν: $\nu F_\nu = \lambda F_\lambda \propto \nu^{4/3}$



total
$F_\nu \propto \lambda^{-1/3}$
star
disk
M_D=4 $M_\odot$
M_D=0.04 $M_\odot$
M_D=10^{-4} $M_\odot$
−0.5
−1
−1.5
−1
0
1
2
3
Log Fν (Jy)
Log λ(μm)

Observed SEDs for typical T Tauri stars



Flat disks do not fit the observed SEDs.

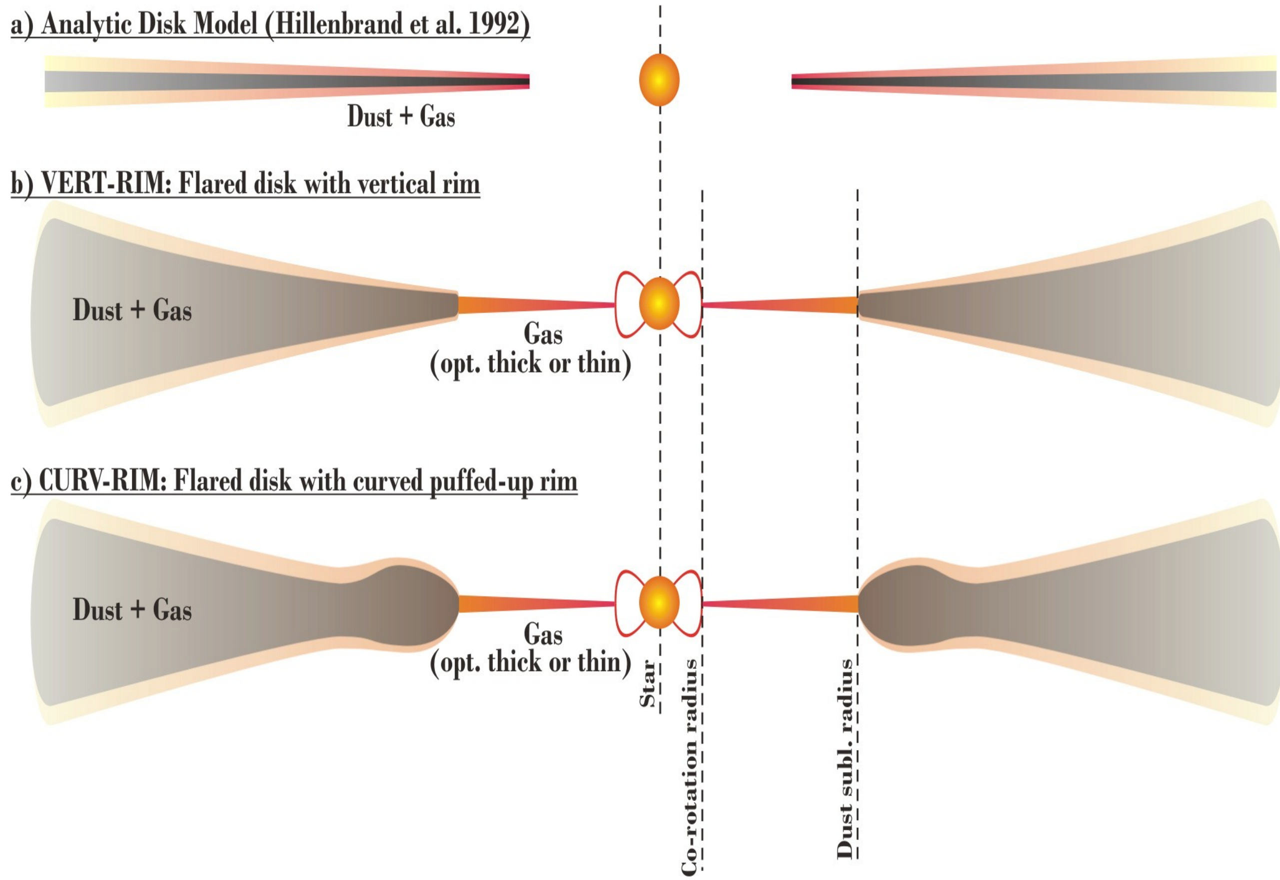
The disks must be flared.

b) Flared disks:

The density structure for disks in vertical hydrostatic equilibrium

$$\rho(r, z) = \rho_0\left[1 - \sqrt{\frac{R_*}{r}}\right]\left(\frac{R_*}{r}\right)^{\alpha} \exp\left\{-\frac{1}{2}\left[\frac{z}{h}\right]^2\right\},$$

where $h(r)/r = c_s(r)/\Omega(r)$ is the scale-height of the disk, assuming the disk is vertically isothermal with c_s and Ω being the isothermal sound speed and rotational velocity, respectively.



(Stefan Kraus etal , Astrophysical Journal 676 (2008) 490)

Chandra observes YSOs

X-Ray Irradiation of Protoplanetary Disks

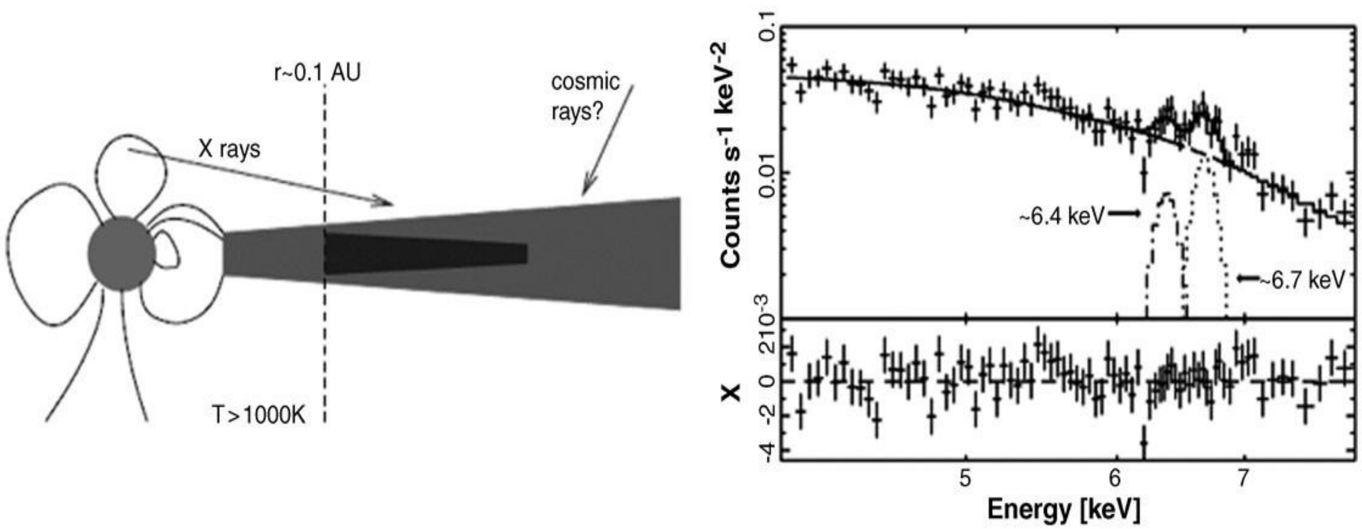
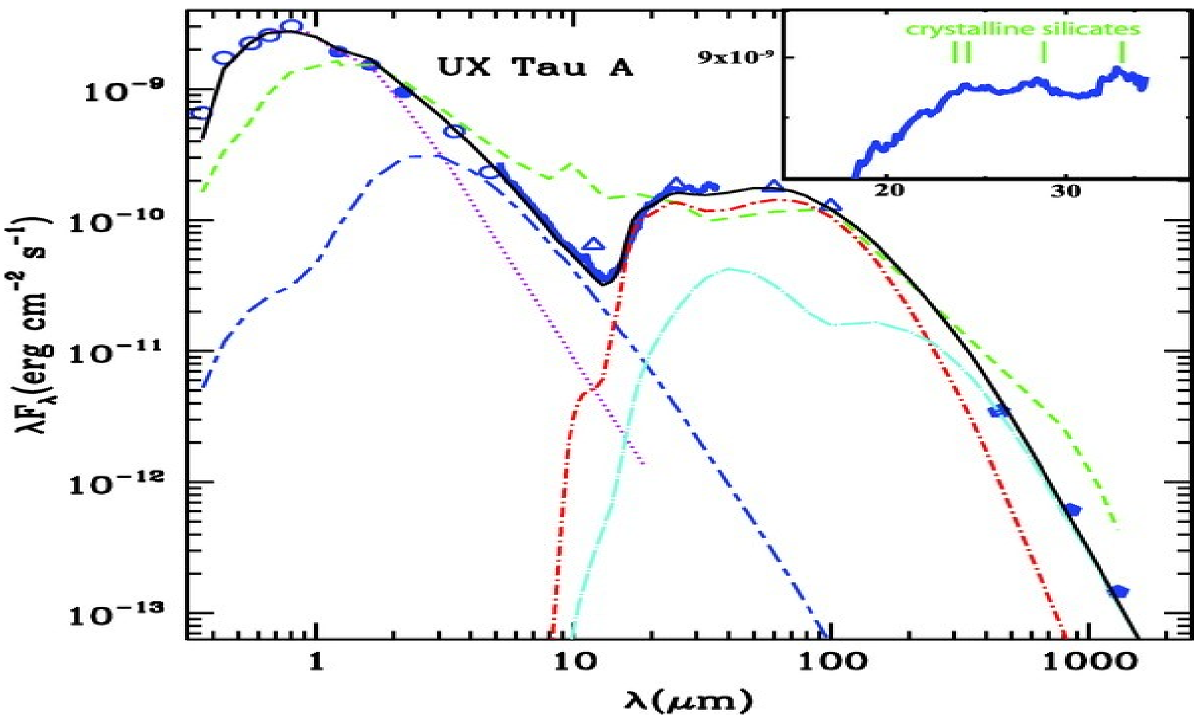


Fig. (Left) Diagram of the irradiation of a planet-forming disk by flare X-rays from the host premain sequence star (36). (Right) Chandra ACIS spectrum of the protostar YLW 16A in the Ophiuchus cloud (d ∼ 140 pc) showing the 6.4 keV fluorescent line from irradiation of cold gas, likely arising from the protoplanetary disk.**(Güdel et al., A&A, 478, 797, 2008)**

Gaps, holes, rims and walls



SED and model of UX Tau A:Separate model components are as follows: stellar photosphere (*magenta dotted line*), inner wall (*blue short-long-dashed line*), outer wall (*red dot-short-dashed line*), and outer disk (*cyan dot-long-dashed line*). We also show the median SED of Taurus (*green short-dashed line*). The inset is a close-up of the *Spitzer* IRS spectrum longward of 16 μm and indicates the crystalline silicate emission features in addition to underlying features from amorphous silicates

(C.Espaillat etal. The Astrophysical Journal, 670:L135-L138, 2007)

General characteristics of observed disks:

1) Sizes: 0.1 - 20 arcsec; 10^1 - 10^3 AU (typical 10^2 AU)
2) Masses: 10^{-3} - 1 Msun (typical 10^{-2} Msun)
3) Temperature: 10^3 - 10^1 K with gradients

The typical disk mass (obtained from mm-wave emission by dust and assuming a gas to dust ratio of 100) is similar to that of Minimum Mass Solar Nebula Models (0.01 Msun).

The disks show:

i) vertical flaring
ii) puffed-up inner edges
iii) holes and gaps
iv) association with outflows
v) association with sub-stellar objects

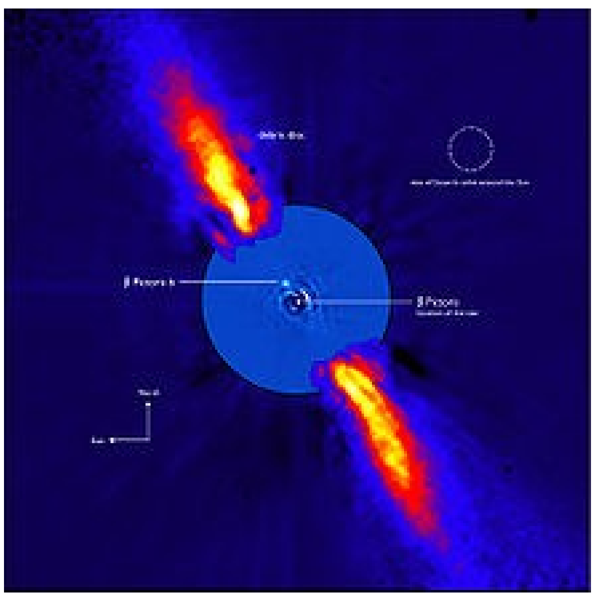
Planets in the disks around stars:

GQ Lup (Neuhäuser et al. 2005) and CT Cha (Schmidt et al. 2008) host rather massive companions, 21.5 MJ and 17 MJ, respectively);

2M1207 (this is a brown dwarf; Chauvin et al. 2004, 2005a) host a 4 MJ mass planet;

UScoCTIO 108 (Kashyap et al. 2008) with a 14 MJ mass planet;

β Pic (Lagrange et al. 2009a,b 2010) has an 8 MJ mass planet. AB Pic (Chauvin et al. 2005b), HR 8799 (Marois et al. 2008) (triple system), SR 1845 (Biller et al. 2006) and Fomalhaut (Kalas et al. 2008) are older planetary systems with ages of about 30 Myr, 60 Myr, 100 Myr, and 200 Myr.



A Giant Planet Imaged in the Disk of the Young Star β Pictoris
A.-M. Lagrange, *et al.*
Science **329**, 57 (2010);

Disks associated with Exo-planetary systems

The first exo-planet around the sun-like star 51 Peg was discovered in 1995 by Mayor and Queloz **378** (6555): 355–359*Nature*

In *a Spitzer*-Based Survey 10 new debris disks around stars with planets were discovered (Ágnes Kóspál et al. The Astrophysical Journal 700 (2009) L73).

Role of disks in the formation of stars and planets

Disks play an important role in formation of stars and planetary systems.

(i) A significant fraction of the matter that makes up the final stellar mass, especially for the lower mass stars, is channelised through the disk.

(ii) Disks regulate the angular momentum evolution of the stars. Magnetospheric accretion and magnetic locking of the disk constrains stellar rotation periods.

(iii) Planetesimals and planetary bodies are formed and evolve within the disk.

Planet Formation:

Now there is general consensus that planets and planetary systems form in the circumstellar disks around YSOs.

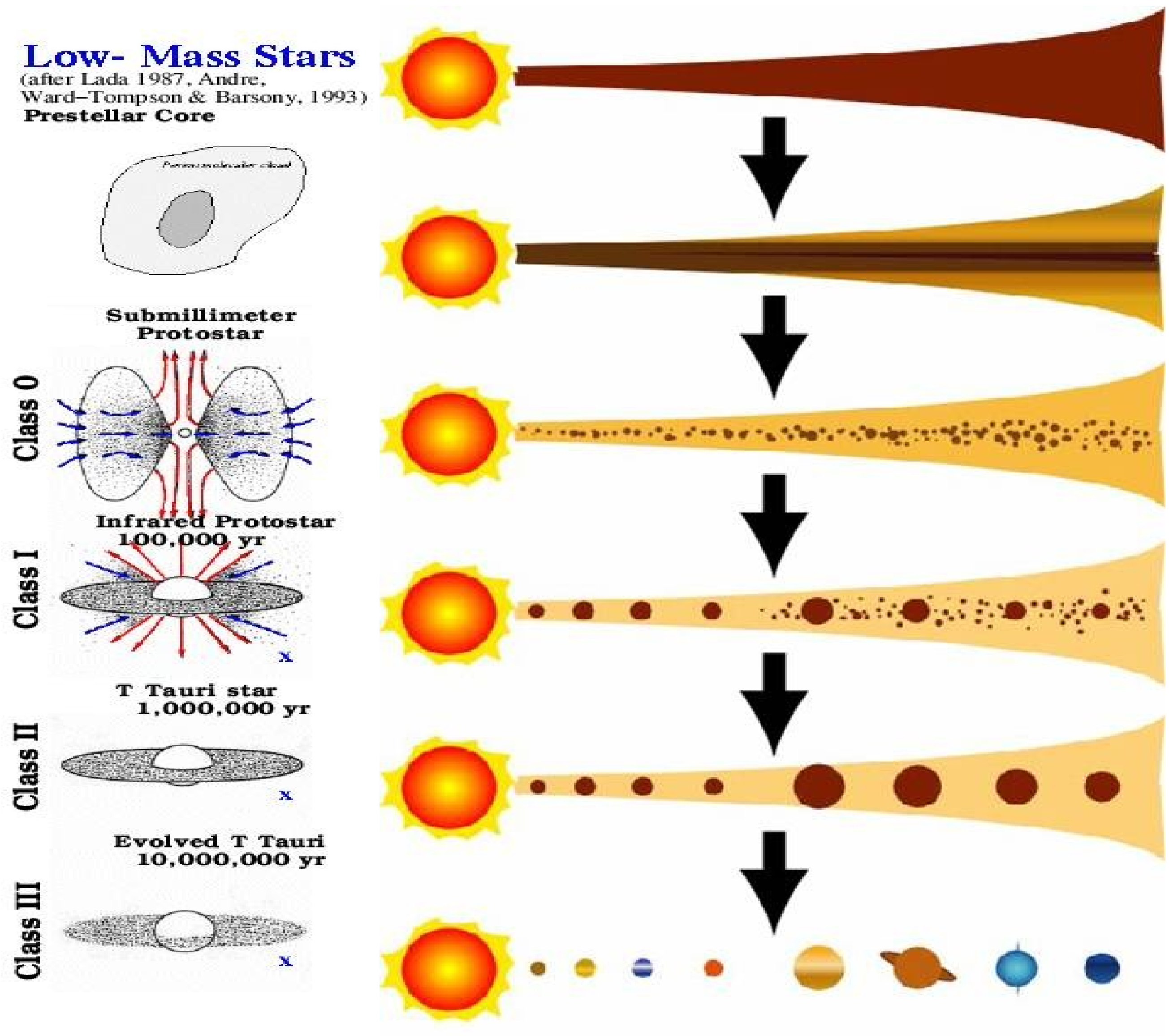
Safronov, V. S. 1972, Akademiia Nauk SSSR Vestnik, 10, 97
Bodenheimer, P., & Pollack, J. B. 1986, Icarus, 67, 391
Boss, A. P. 2001, ApJ, 563, 367

(a) Dust grain growth and sedimentation (size up to cm range in 10^4 y)

(b) Planetesimals 0.1 – 1 km size, 10^5 y (mechanism to prevent inward radial drift unclear)

(c) Planetary cores 1000 km – earth size, 10^6 y (by gravity assisted growth)

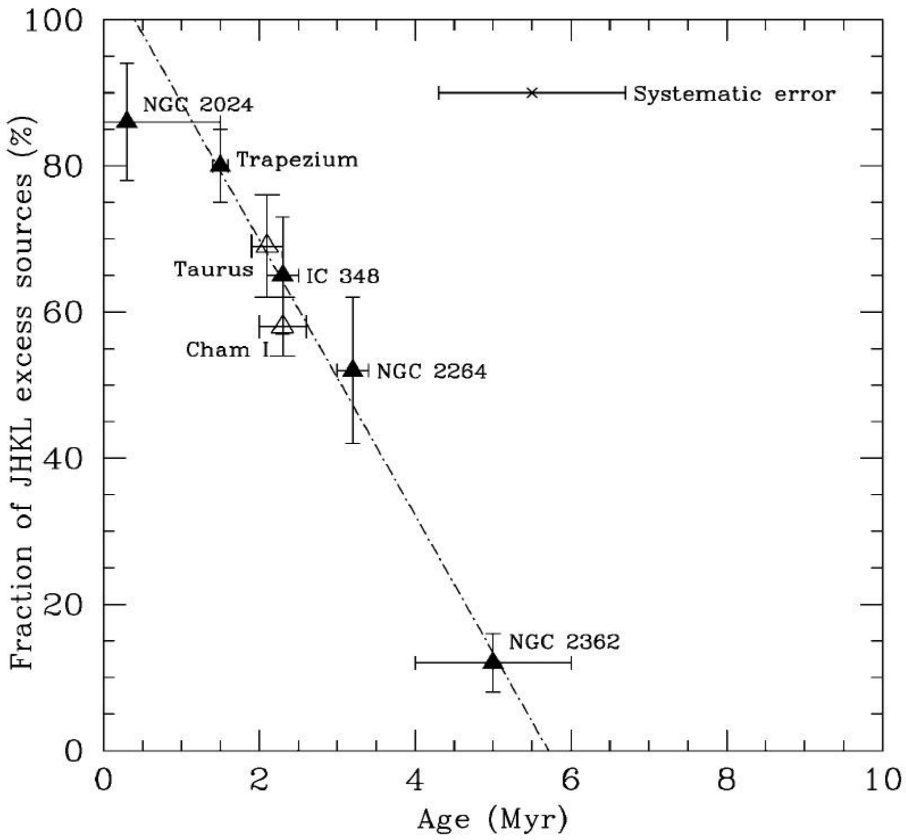
(d) Giant planets: in the outer disk 10^7 y; (i) (10 earth cores+accretion) (ii) gravitational instability



Stages in the Star and Planet formation process

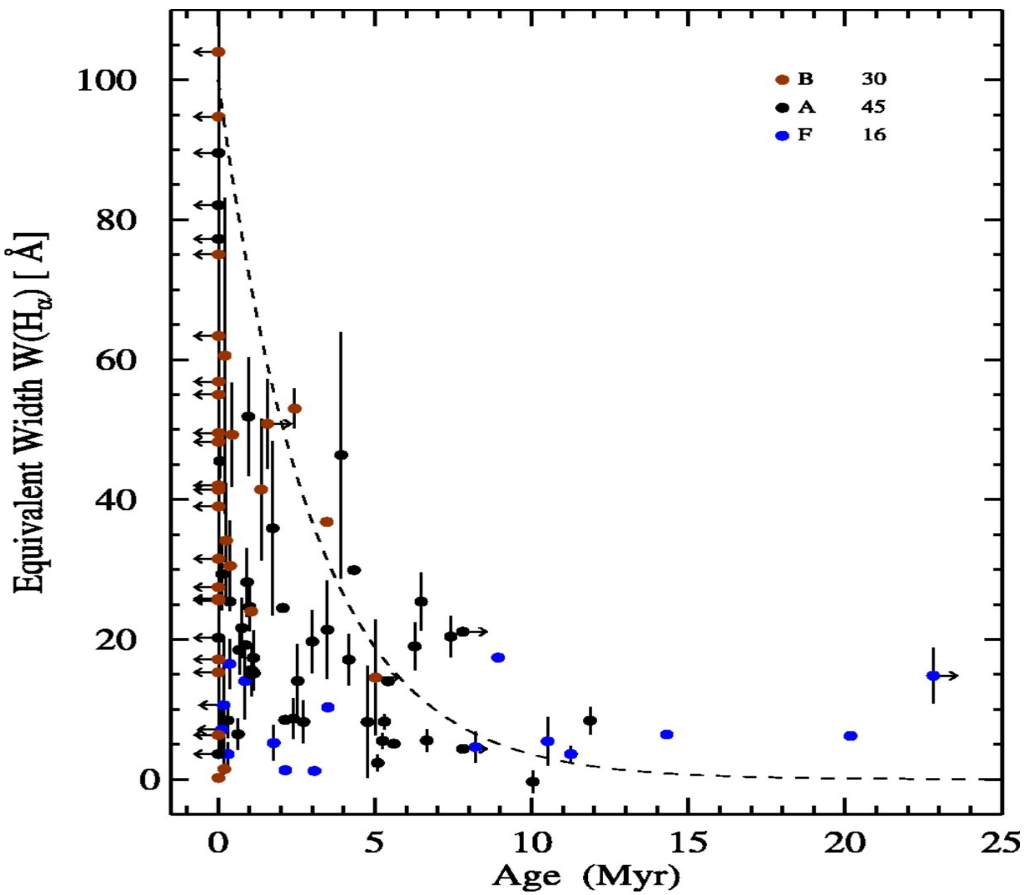
Disk Evolution and constraints on planet formation:

Disk frequency in star clusters:



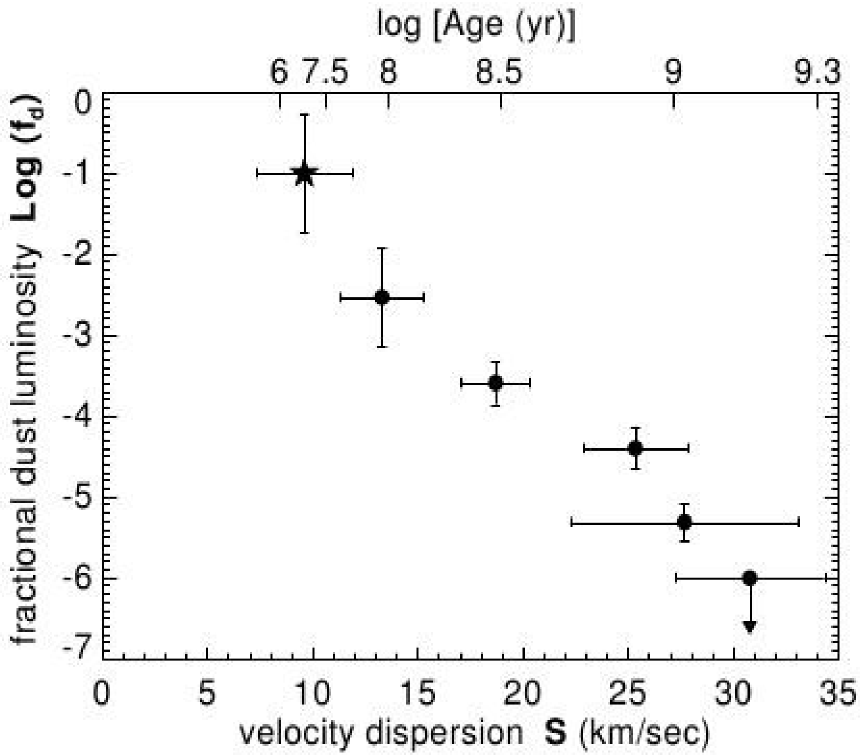
Disk fraction as a function of cluster age for a sample of young clusters with consistently determined mean ages. (Haisch KE, Lada EA, Lada CJ. 2001. Ap. J.Lett. 553:L153–56.)

Evolution of H_α emission strength (accretion rate)



H_α equivalent widths of HAeBe stars plotted against derived stellar ages. The dashed line is of the functional form $W(\text{age}) = W(0)\exp(-\text{age}/\tau)$, with $W(0) = -100$ and $\tau = 3$ Myr. **(Manoj, P; Bhatt,H.C.; Maheswar, G.; Muneer S. 2006ApJ...653..657)**

Evolution of dust optical depth $\tau_d = L_{ir}/L_*$



Filled circles represent Vega-like stars. Herbig Ae/Be stars are represented by the solid star symbol. **(Manoj P & Bhatt H.C. A&.A. 429 (2005) 525-530)**

Disk evolution

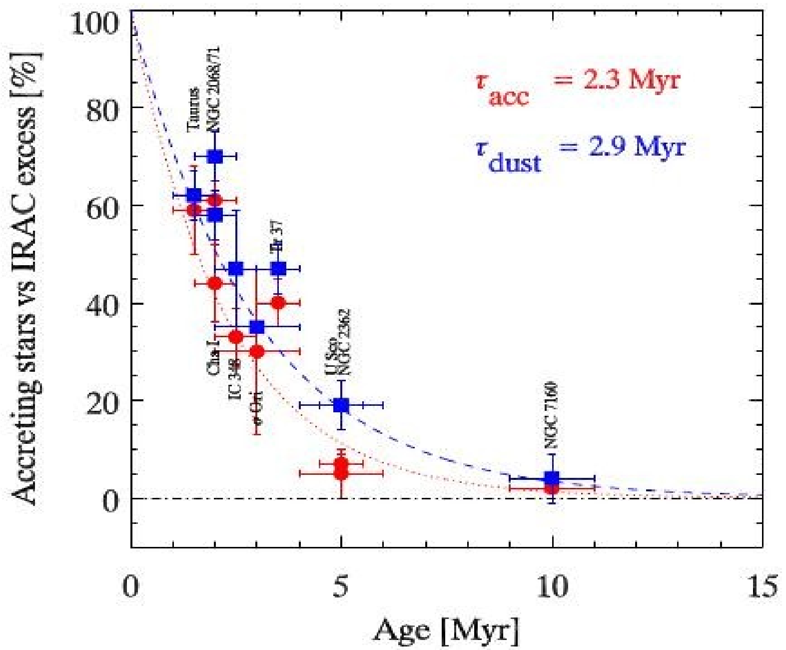


Fig. 4. f_{acc} (dots) versus f_{IRAC} (squares) and exponential fit (dotted line for f_{acc}, dashed line for f_{IRAC}.

Fedele, D.; van den Ancker, M. E.; Henning,Th.; Jayawardhana, R.; Oliveira, J. M. [2010 A&A 510A, 72]

THERE IS VERY LITTLE TIME FOR PLANET FORMATION!!!

The Future

1.Studies of gas in the disk

Most studies of protoplanetary disks have been in the infrared which is emitted by dust (a minor component) in the disk. Gas, the major component of the disk, has to be studied primarily by using molecular spectroscopy. In particular, gas provides the only diagnostic tool that can be used to study disk dynamics and chemistry.

2.Studies at higher resolution

Angular scale of a typical YSO disk in nearby star forming regions (100s pc): 1 AU at 100pc is 0.01 arcsec. Structures in the disk, especially the inner planet-forming regions, gaps, holes, radial and vertical gradients would need high resoluion.

3.Variability studies

Dynamical time scales in the disk : 1(R/AU)^1.5 yr. Multi-epoch observations need to study changes in the disk structure.

4. **Models**

Improved models and (3D) numerical codes that can produce high resolution images and spectra, incorporate accurate dust opacities, phase function , polarization and physical processes like gas turbulence, photo-evaporation, dust sedimentation etc.

New and upcoming facilities like Herschel Space Observatory, SOFIA, ALMA, JWST, ELTs can be expected to significantly improve our understanding of YSO disks and their role in the formation of planetary systems.

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