The Evidence for Solar System Sized Accretion Disks around Stars and the Process of Planet Formation

Debra Shepherd
National Radio Astronomy Observatory
Socorro, New Mexico USA
How Stars & Planets Form

I. Stars form from disks of gas & dust. This process is regulated by ejecting gas in “jet-like” outflows.

II. Planets form later from the remnants of the disk. Planets may only form when conditions around the star are “just right.”

III. Planets have been detected around other stars. Current detection methods are limited to finding large gaseous planets like Jupiter.
Introduction: The Formation Process

For a “T-Tauri” star – how our Solar System formed

Scales:

- Earth sun distance = 1 AU, Astronomical Unit (6 lt minutes)
- Size of our Solar System = 80 AU (8 lt hours)
- Size of typical accretion disks = 100 AU
- Size of typical outflow = 1 parsec (pc) = 3.26 lt yrs = 200,000 AU
- Closest star to Sun = 4.3 lt yrs = 1.3 pc (α Centauri)
Linked Accretion & Outflow

Disk regulates accretion, acts as launching point for outflow. Disk remnant becomes planetary system.

Outflow carries away excess angular momentum from spinning cloud. Without outflow, star would rotate to “break up” speed and fly apart – no stars, no planets.

2 basic theories:

X-wind
(Shu and collaborators) – schematic shown.
Protostar magnetic field links with disk field to control infall & outflow.

Disk-winds
(Konigl, Pudritz, Garcia, & collaborators).
Star does not have a magnetic field, disk field controls outflow over a range of radii.
Stars form within dense interstellar clouds of gas & dust that obscure our view at visible wavelengths.


The Horsehead Nebula, *HST Heritage project*
Accretion/Outflow – Low Mass

**Top:** Embedded outflow/accretion system HH 211: CO (molecular outflow), H$_2$ (shocks), & 1 mm (230 GHz) continuum (warm dust) (McCaughrean et al. 1994, Gueth & Guilloteau 1999).

**Right:** An older object HH 111: IR & visible light (HST) showing jet & nebula above edge-on accretion disk (Reipurth et al. 1997, Reipurth & Bally 2001).

**HH 30:** Visible light (HST R band) showing jet & reflected light from surface of flared disk (Watson et al. 2000).
Accretion/Outflow – Intermediate Mass

IRAS 20126+4104: visible light shows cloud boundary & where flow breaks out (arrow), contour outlines = red & blue-shifted CO outflow, + symbol = protostar (Shepherd et al. 2000).

2000 AU torus (Cesaroni et al. 1999), inner disk not detected (but it is probably there).

Flows from more massive protostars tend to be less jet-like.

NO inner accretion disk detected toward a protostar more than 10 times the mass of the Sun

Focus here on low & intermediate mass stars.
G192.16-3.82

Shocks in [SII] emission. Outflow escapes cloud, extends more than 10 pc from end-to-end. 
D = 2 kpc (7000 lt yrs)

Red & blue-shifted CO(J=1-0) emission,
100 $M_{\text{sun}}$ outflow material

Mass outflow rate:
$\sim 6 \times 10^{-4} \ M_{\text{sun}}/\text{yr}$

$\Rightarrow$ Mass accretion rate likely to be greater than $\sim 10^{-3} \ M_{\text{sun}}/\text{yr}$
G192.16-3.82 – Inner Accretion Disk

Very Large Array + Very Long Baseline Array Pie Town Antenna observations of inner-most region surrounding massive protostar (40 AU resolution at 2 kpc (7000 lt yrs)).

7 mm (43 GHz) continuum emission from ionized gas and warm dust (Shepherd et al. 2001).

Contours: observations

Color: model of accretion disk, central star, outflow, & companion protostar:

8 $M_{\odot}$ protostar

3-20 $M_{\odot}$ disk

Outflow with 40° opening angle.
G192.16-3.82 – Artist view

Massive protostar with 130 AU diameter accretion disk and wide-angle outflow.

Close binary companion, 100 AU separation – truncating inner disk?

Circumbinary torus – inferred from water maser emission.

Well-collimated jet (mixed thermal and synchrotron emission), actual location of protostar producing jet is unknown.
G192.16-3.82 - Disk Stability

Gravitational instabilities expected to be prevalent if $M_d > 0.3 \, M_*$ (Laughlin & Bodenheimer 1994). Toomre Q stability parameter (Yorke, Bodenheimer, & Laughlin 1995):

\[
Q \equiv \frac{c_s \Omega}{\pi G \Sigma} = 56 \left( \frac{M_*}{M_\odot} \right)^{\frac{1}{2}} \left( \frac{R_d}{\text{AU}} \right)^{-\frac{3}{2}} \left( \frac{T_d}{100 \, \text{K}} \right)^{\frac{1}{2}} \left( \frac{\Sigma}{10^3 \, \text{g cm}^{-3}} \right)
\]

$C_s = \text{local sound speed, } \Omega = (GM_*/r^3)^{1/2} = \text{epicycle frequency of disk,}$

$\Sigma = (M_d/\pi R_d^2) = \text{disk surface density, } R_d \& T_d = \text{disk radius \& temperature.}$

For $Q < 1$, disk susceptible to local gravitational instability and axisymmetric fragmentation. Could be significant angular momentum transport mechanism and/or affect planet development.

130 AU diameter accretion disk in G192.16-3.82:

$M_* = 8 \, M_{\text{sun}}, \, T_d = 100 \, \text{K}, \, R_d = 70 \, \text{AU, \& } M_d = 3 \, M_{\text{sun}}, \, Q \sim 0.5$ (uncertainties high for $T_d \& M_d$).

➔ Disk locally unstable. May affect planet formation…
Difficult to Form Planets?

Reasons why it may be difficult to form planets:

- Disk turbulence.
- Ionizing radiation: once cluster massive stars “turn on”, disk gas is destroyed (no more Jupiters).
- 60% of Solar type stars are binaries $\Rightarrow$ accretion disks are generally smaller (Jensen, Mathieu & Fuller 1994, 1996).
- Protostar interactions could destroy disks. Simulation: 50 $M_{\text{Sun}}$ cloud, 0.4 pc diameter, hydrodynamics code, 3.5 million particles, 100,000 CPU hrs on 64 processors (Bate et al. 2002).

A copy of Matthew Bate’s impressive simulation can be obtained from: www.astro.ex.ac.uk/people/mbate/Research/pr.html
Visible nebula created by reflected light from “Trapezium Cluster” of hot, massive stars. Low-mass stars are still forming near massive stars.
The 3-D Structure of Orion

Simulation developed by San Diego Supercomputing Center & Hayden Planetarium
Disks in the Orion Nebula

Irradiated by the Trapezium stars (left) & in silhouette against bright nebular emission (bottom).
Bally, O’Dell, McCaughrean 2000

Translucent edge in disk: Measured opacity at 3 wavelengths ➔ large grains (cm sized – protoplanetary?) (Bally et al. 2002)
The disk velocity in LkCa 15 traced by CO and chemistry traced by HCN, Owens Valley Interferometer (Qi et al. 2001)

Disk sizes ~100 AU, $M_d \sim 0.03 \, M_{\text{sun}}$ (Sargent et al. 1986, Dutrey et al. 1997, Looney et al. 2000)

T-Tauri Disks
Mean Velocity traced by CO
Koerner & Sargent (1999)
Debris disks are remnant accretion disks with little or no gas left (just dust & rocks), outflow has stopped, the star is visible.

**Theory:** Gas disperses, “planetesimals” form (100 km diameter rocks), collide & stick together due to gravity forming protoplanets (Wetherill & Inaba 2000).

Protoplanets interact with dust disks: tidal torques cause planets to migrate inward toward their host stars. Estimated migration time ~ $2 \times 10^5$ yrs for Earth-size planet at 5 AU (Hayashi et al. 1985).

Perturbations caused by gas giants may spawn smaller planets (Armitage 2000):

- Start with a stable disk around central star.
- Jupiter-sized planet forms & clears gap in gas disk.
- Planet accretes along spiral arms, arms become unstable.
- Disk fragments into more planetary mass objects.
Clusters as Chronometers – RWC 38

As star forming region ages, stars become visible.

Identify all stars in cluster & assume same age.

Count stars with debris disks: excess IR emission due to warm circumstellar dust.

Repeat with clusters at different ages to estimate lifetime of typical disk.

Only 1 debris disk around 2x5 M_{sun} binary star system found (Kalas & Jewitt 1997, Lecavelier des Etangs et al. 1998), none detected around more massive stars → massive star disks dissipate faster.

RWC 38 at 2μm ~1400 stars

(Alves et al. 2002)
Frequency of Protoplanetary Disks

Star forming clusters with well determined ages.

Measure fraction of stars with IR excess (disks) – plot versus age to give disk lifetime.

Near infrared data ➔
Half of all stars lose disks by 3 Myr
90% of stars lose disks by 5 Myr!!

Haisch, Lada, & Lada 2001
Alves, Lada, Lada, Muench, Moitinho 2002
Disk Fraction $f_d$ versus Age

$$f_d = \frac{L_{\text{ex}}}{L_{\text{star}}}, \quad L_{\text{ex}} = \sum (12, 25, 60, 100 \mu\text{m fluxes} + c)$$

Dust mass $\propto f_d \propto 1/(\text{age})^2$

Far infrared data $\Rightarrow$
Low mass dust disks may persist for a billion years.

Spangler et al. 2001
Debris Disks – Outer Disk

AB Aurigae outer debris disk nearly face on – see structure & condensations (possible proto-planet formation sites? Very far from star).

(Grady et al. 1999)
Debris Disks – Near Solar System Size

SCUBA/JCMT & OVRO Imaging of Vega
(7.8 pc/25 lt yrs from earth)

\[ \lambda = 0.85 \, \text{mm} \quad \lambda = 1.3 \, \text{mm} \]

Holland et al. (1998)

Koerner, Sargent, & Ostroff (2001)

Semi-major axis of Pluto = 40 AU
Debris Disks – Inner Disk

Solar type (T-Tauri) star/disk

T Tauri & Herbig Ae disk cartoons for passive disk geometry (no accretion or outflow).

R_{inner} \sim 0.3 \text{ AU (Mercury Orbit). (Dominik et al. 2002)}

\sim 2-3 \ M_{\text{sun}} \ A \ type \ star/disk

Side view schematic of A type star/disk
The Only Debris Disk Ever Detected around a B5V (5 $M_{\text{sun}}$) Star: BD+31°643

Kalas & Jewitt (1997) detect 6000 AU debris disk around binary $2 \times 5 M_{\text{sun}}$ star system (distance = 330 pc/1000 lt yrs). Lecavelier des Etangs et al. (1998) show radiation pressure will blow dust out of system fast.

We may be seeing dust outflow mechanism! Not a stable debris disk making protoplanets like the 1000 AU Beta Pic disk. The dust could still be produced by planetesimals hitting each other, but the system will eventually evaporate due to higher radiation pressure.

Does this mean planets can only form around solar type stars???? Maybe…

Lada et al. (UF FLAMINGOS)

Lifetime~1000yr
Mass~0.1% $M_{\text{Jup}}$
Evidence for Extra-Solar Planets

Two detection methods available to infer existence of planets around solar type stars:

- Measure star wobbles due to gravitational tug of planet on star
- Image perturbations in debris disks

Methods preferentially detect large planets near the star (e.g. Jupiter-sized planets less than 1 AU from star). We cannot detect Earths yet.

Recently, an additional method has become possible to probe other characteristics of the planet:

- Monitor known planetary systems for star transit events
Extra-Solar Planets – “Star Wobbles”

Measures lower limit on mass: \( M \sin(i) \) where \( i = \text{unknown inclination of orbit} \) & \( M = \text{mass of planet} \) (Marcy 2000)

More than 70 gas giant planets discovered so far.
Beta Pictorus (100 million years old) debris disk: Inner debris disk orbits in a different plane than outer disk.

Dust particles collide & get blown out by radiation pressure or accrete onto star ➔ warp should not last less than 10 Myrs.

Something must continuously twist the disk. A Jupiter-sized planet in an inclined orbit could do this. (Burrows, Krist 1996)

**Simulation** (Burrows, Krist 1996)

**Zoom in:** A Jupiter-mass planet in Jupiter orbit. Planet orbit is in disk plane, no warp seen.

**Zoom out:** planet is now inclined 3° with respect to outer disk plane. Inner disk is now warped.
Dust rings around stars – something is clearing dust out regions of debris disk: most likely explanation: planet/protoplanet.

Weinberger, Becklin, Schneider (1999)

Schneider et al. (1999)
Extra-Solar Planets – Planet Transit

When planet passes in front of parent star, starlight is dimmed & some light must pass through planetary atmosphere.

Spectral signature of atmosphere in planet around HD 209458 measured:


The detection opens new frontier to find chemical elements such as oxygen, the signature of life, on other planets.

Credit: A. Field, STScI
Where Do We Go From Here?

Refine current methods & build new instruments such as:

**Very Large Telescope Interferometer (VLTI) with Phase-Referenced Imaging & Micro-arcsecond Astrometry (PRIMA)** – Array of mid-IR (10-20µm) telescopes being built in Chile, PRIMA available in 2005. Will be able to solve for inclination of planet orbit ($M_p \sin(i) \Rightarrow M_p$).

**Atacama Large Millimeter Array (ALMA)** – World wide project to be completed in 2010. Image accretion & debris disks, trace velocity structure, map 5 AU gaps in the disks where planets may be forming.

**Space Interferometry Mission (SIM)** – scheduled for launch in 2009, using optical interferometry, SIM will determine stellar positions & distances 100s of times better than now possible \(\Rightarrow\) can search for Earth-sized planets.

**Terrestrial Planet Finder (TPF)** – Will be designed to image planetary systems & debris disks. TPF will be either a coronagraph, a large-baseline interferometer operating in the infrared, or perhaps a combination of the two architectures. Final selection of a TPF architecture will occur in 2006.
Stars form within dense clouds of molecular gas from disks of gas & dust. Disks regulate accretion onto the star & act as a launching point for the outflow. The outflow carries away excess angular momentum.

Planets form later from the remnants of the disk (debris disk). Stable debris disks that appear to have the “right conditions” to form planets have only been detected around stars that are like our sun or have lower mass.

Planets have been detected around “solar-type” stars but we have not imaged a planet yet. Current detection methods are limited to finding large gaseous planets like Jupiter.

The next generation of telescopes will have the sensitivity & resolving power to detect Earth-sized planets and allow us to study how they are formed.
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http://www.nrao.edu/~dshepher/science.shtml

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National Radio Astronomy Observatory
Socorro, New Mexico USA
More information about planets and the search for life

Here be Dragons: The Scientific Quest for Extraterrestrial Life
By Koerner & LeVay
Oxford University Press 2000