Lynne A. Hillenbrand

- Galactic and Local Star Formation
- Circumstellar Disks and Outflows
- Planet Formation and Detection

[with attention to the radio angle]
Galactic Star Formation

Most stars form in Giant Molecular Clouds.

- $10^4 - 10^{6.5} \, M_{\text{sun}}$
- 10s - 100 pc
- 50-100 cm$^{-3}$
- 10 - 30 K
- $\sigma_{\text{vel}} = 2-4 \, \text{km/s}$
- $|B| = 3-30 \, \mu \text{G}$

$dN/dM \propto M^{-1.6}$

Sanders et al (1986)
$M_{\text{molecular}} = 3 \times 10^9 \, M_{\text{Sun}}$
Local Star Formation

[North American / Pelican Nebulae] 2MASS
Traditional Radio Obs / Star Formation

- Cloud/core chemistry [Orion]
- Heavily extincted regions [Galactic Center]
- Ionized gas (HII regions) [W49]
- Masers in disk/outflow [NGC 2071]
Radio Continuum / Star Formation

Star Forming Regions:
- Free-free emission from e.g. SN remnants, HII regions
- Gyrosynchrotron from large scale magnetic fields
- Thermal emission from embedded, clustered sources

Individual Young Stars:
- Free-free emission from ionized outflows
- Gyrosynchrotron/Brehmstrahlung from magnetospheres
- Thermal emission from circumstellar disks
Local Star Formation

- Most - but not all - stars form in aggregates and clusters.
  - **Aggregates** (unbound)
    - 10’s of stars
    - 0.1 - 0.5 pc radius
    - $<10^2$ stars / pc$^3$
  - **Clusters** (may be bound)
    - 100’s to 1000’s of stars
    - 0.5-5 pc radius
    - $10^3 - 10^5$ stars / pc$^3$
    - evidence for prolate shapes

- Most clusters are small, but most of the total stellar mass is in the big clusters.
Observed Cluster Properties: Quantitative Clustering

- Mean Surface Density of Companions
  - “binary/multiple regime”: constant slope
  - “clustering regime”: different slopes
  - break point related to stellar density?

- Differences in IMFs between regions are not as dramatic as differences in MSDCs, so relationship to Jean’s mass is not obvious *(Larson, 1995)*

- Simulations show that break points correlate with \( r_{\text{core}} \) and \( r_{\text{half mass}} \) *(Klessen & Kroupa 2001)*

*Simon (1997)*
Observed Cluster Properties: Structure and Mass Segregation

Hillenbrand & Hartmann (1998)

- ONC
  - surface density implies $\rho \sim 1/r^2$
  - cluster is near virial equilibrium
  - but only a few crossing times old
  - mass segregation must be primordial, i.e. part of the clustered star formation process
Observed Stellar Properties

- High and low mass stars form in the same place at the same time.
- Star formation is coherent within $<1-2$ Myr.

[Orion Nebula Cluster]
The Stellar and Sub-Stellar Initial Mass Function

Distribution of masses rises as $dN/dM \propto M^{-[2.3 - 0.3]}$ with the slope flattening towards lower masses and extending in a continuous manner into the brown dwarf regime.

Debate over IMF invariance

- data do show evidence for regional variations but statistical fluctuations are not necessarily exceeded
- extremes do not reveal the expected trends/biases in the emergent IMF with
  - metallicity (LMC, globular clusters, solar)
  - stellar density (3-4 orders of magnitude)
  - cloud temperature or pressure
  - age (<1 Myr to >12 Gyr)
What Next?

- We know a lot about statistics of clusters and stars (though not nearly enough, of course).
- The next steps are to trace the resulting cluster/star properties back to the cloud initial conditions.
- How to observe the earliest stages of star formation?
  - longer wavelengths == more self-embedded objects
  - need to distinguish thermal from nonthermal emission
Core to Star IMFs?


[Ophiuchus] Young et al. (2006)
Pre-main Sequence Evolution

Cloud collapse

10^4 yr

Planetary system

10^9 yr

Main sequence

Disk/wind

10^5 yr

Planet building

10^7 yr

100 AU

T_{\text{star}} (K)

L_{\text{star}}

8,000

5,000

2,000

Beckwith & Sargent
Before/During Collapse

\[ \rho(r) \propto r^{-[2 - 1.5]} \]

\[ r_{\text{infall}} \leq 0.1 \text{ pc} \]

Alves, Lada, Lada

[Image of a star field with a dark cloud and a graph showing the relation between magnitude and radius, with \( \xi_{\text{max}} = 6.9 \pm 0.2 \).]
Regulation of Core Collapse

- Support against collapse:
  - Thermal pressure
  - Magnetic pressure
  - Turbulence

- Instigators of collapse:
  - Gravity
  - Triggering shocks

can constrain importance of various mechanisms through measurement of
  - B-field morphology
  - core mass/flux ratio

[Crutcher]
Emerging Protostars

The edge-on disk of a Class I YSO, IRAS 04302 +2247, in molecular line and scattered light emission. Contours of $^{13}$CO(1-0) emission at OVRO are superimposed on a three color NICMOS image of the source. There is excellent correspondence between the molecular gas disk and a dense absorption lane. Extended nebulosity is attributed to scattered stellar light in a surrounding envelope. (Padgett et al. 1999)
Quantifying Spectral Energy Distributions

Evolution in age?

vs.

Evolution in circumstellar environment?
Optical to Radio SEDs of Protostars

Eisner, Hillenbrand, Wolf + literature
Radio Emission from Young Objects

Thermal (sub-mm/mm) ==> free-free (cm)


$M_1 + M_2 = 1.2 \, M_{\text{sun}}$ (but 30 $L_{\text{sun}}$)
Protostellar and YSO Outflows

- Generate cloud turbulence
- Remove angular momentum
Masers in Protostellar Jets

- H$_2$ vs SiO
- Entrainment?

Chandler et al (2005)
Disk Structure

Dust-structure of disk

- layer of larger dust grains
- hot dust surface layer
- colder midplane

Gas structure of disk

- CO layer, no H2 yet
- intermediate warm layer; rich molecular chemistry
- freeze-out of molecules

Dust condensation radius
Evolution of Circumstellar Disks

- Disk evolution:
  - SED changes with time
  - \( M_{\text{accretion}} \) decay with time
  - \( M_{\text{dust}} \) decrease with time
  - changes in grain properties (composition, size)

Malfait et al. (1998)
Disentangling Thermal and Free-Free

cm wavelengths are sensitive to large (mm => cm) sized grains

Example: TW Hya (10 Myr)

**Krist et al. (2002)**

- $R_{\text{min}} = 4 \text{ AU}$
- $R_{\text{max}} = 140 \text{ AU}$

**Roberge et al. (2004)**

- $a_{\text{min}} < 1 \mu m$
- $a_{\text{max}} = 1 \text{ cm}$

**Calvet et al. (2002)**

**Wilner et al. (2005)**
Imaging Newly Formed Planets

Figure 7. A numerical simulation of a Jupiter mass planet within a disk that opens up a gap in the disk through tidal interaction (from [29]). The dark region in this surface density plot is nearly devoid of disk material. The planet is located within the dark region, in a small accretion stream. While the planet itself is extremely difficult to detect at any wavelength, the wide gap provides a strong marker of its presence, and the gap structure might be used to constrain its properties.

First Spatially Resolved Debris Disk Surrounding Young Solar Analog

HD 107146 at 200 +/- 100 Myr

\[ T_{\text{dust}} = 60 \, \text{K} \implies R_{\text{in}} = 30 \, \text{AU} \]
Extrasolar Planet Detection

http://www.nasm.si.edu/

- 50 kJy at d=4.5 AU
- 0.2 uJy at d=10 pc
Extrasolar Planet Detection

[Lazio et al. 2004]
The Inner Disk

Mahdavi and Kenyon (1998)

[Hartmann 1998]

- accretion
- outflow

[Camenzind 1990]
Constraints on Inner Gap Sizes

Muzerolle et al. (2004)

Spectro-photometry from IRTF/SPEX

$T_{\text{dust}} = 1400 \text{ K}$ → $r_{\text{gap}} = 0.05-0.2 \text{ AU}$

Interferometry from PTI

Eisner et al. (2003, 2004)
Magnetic Field and Outflow Geometry

Fig. 1. Left: A rotating disc embedded in a magnetic field induces a current leading to a magnetic braking (Barlow's wheel; see e.g. http://www.sparkmuseum.com/MOTORS.HTM for many illustrations). Right: A MAES can be seen as two independent electric circuits, each corresponding to a jet. Asymmetric jets can thus be easily achieved, even with a symmetric poloidal field.

Fig. 2. Axisymmetric jets are made of magnetic surfaces of constant magnetic flux nested around each other and anchored in the disc. Each surface behaves like a funnel whose shape depends on the transfield equilibrium. Solving the jet equations requires to specify several quantities (see text).

Ferreira (2006)
Outflow Launching Mechanism

Ferreira et al. (2006)

Fig. 1. Top: Classes of published stationary MHD jets for YSOs. When the magnetic field is threading the disc on a large radial extension (a: extended disc wind) or a small disc annulus (b: X-wind), jets are accretion-powered. They are mostly pressure-driven when the field lines are anchored onto a slowly rotating star (c: stellar wind). The corresponding Alfvén surfaces $S_A$ have been schematically drawn (thick lines). In the X-wind case, two extreme shapes have been drawn: convex (solid line) and concave (dashed). Bottom: Sketch of the two possible misaligned magnetospheric configurations: (d) X-type neutral line driving unsteady Reconnection X-winds, when the stellar magnetic moment is parallel to the disc field; (e) Y-type neutral line (akin the terrestrial magnetospheric current sheet) when the stellar magnetic moment is anti-parallel (or when the disc field is negligible). (f) A CME-like ejection is produced whenever the magnetic shear becomes too strong in a magnetically dominated plasma. Such a violently releasing event may occur with any kind of anti-parallel magnetospheric interaction (even with an inclined dipole). The thick lines mark the zones where reconnections occur.
Tracing the Origin of Outflows

[S II] 6717/6731 Å (top)
H₂ 2.12 μm (bottom).

He I 10830 Å line profiles

\[\text{Velocity (km s}^{-1}\text{)}\]

Noriega-Crespo et al. 2001
Edwards et al. 2006
V1647 Ori: A Young Star “TOO”

- EX-Ori type event lasting ~2 yr.
- Correlation of X-ray with optical/infrared flux.
- X-ray spectrum hardened during outburst.
- Suggests substantial reorganization of magnetic field structure during significant accretion events.
- Radio??

Kastner et al. (2006)
Stellar Astrophysics at cm / m Wavelengths

- Slow variation: cyclic / long term / sunspots
- Rapid variation: irregular / short term / flare
- Stellar winds

- Spatially resolve magnetic structures? - size vs lambda
- Physical processes within magnetospheres / coronae / chromospheres of other stars.
Young Star Variability

- Near-ubiquitous phenomenon from ~0.3-2 um
  - Cool spots (like sun)
  - Hot spots (due to accretion)
  - Line-of-sight extinction
  - Irregular color-mag

- Relatively independent of coronal x-ray flaring behavior

- Radio correspondance?

Stassun et al. (2006)
Brown Dwarfs and Low Mass Stars

- Magnetic fields!
  - Zeeman splitting of optical/infrared lines  
    $\Rightarrow |B| = 1-3 \text{ kG}$
  - X-ray and radio flares  
    $\Rightarrow 10^6-10^7 \text{ K gas}$

Fig. 5.— High resolution spectra of the inactive star GJ 1227 (M4.5, lower black line) and the active star Gl873 (M3.5e). In order to compare the spectra, we artificially enhanced the absorption strength in Gl873 and spun up the spectrum of GJ 1227 (see text). For comparison, the sunspot spectrum is overplotted with an offset. Magnetically insensitive lines are highlighted in blue, sensitive lines in green. Positions of atomic lines are marked as hatched regions.

[Osten et al. (2005)]

[Reiners & Basri (2006)]
Many radio bright low mass objects

During flares expect:

\[ L_R(t) \propto \frac{d}{dt} L_X(t). \]

[Gudel; Berger et al. (2005)]
Standard Stellar Winds
Proper Motions ==> A Stellar Parallax!

D = 149.0 +/- 0.8 pc

Top level science:
- Cloud/core chemistry
- Follow cluster and star formation process
- Image disks and outflows
- Detect planets
- Stellar astrophysics