AST SPECIAL TOPICS: EXOPLANETS
MISC. LECTURE NOTES: SPRING 2018

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Week 8: Star formation and protoplanetary disks

Star formation and early stellar evolution: the briefest overview ever.

- CO and dust: the observational view of star formation sites in the Galaxy
  - In terms of composition and mass, star-forming clouds are mostly cold ($T \sim 10 - 100$ K) H_2 — but you can't detect it! (*Why?*) So emission from CO, the next most abundant molecule ($N(\mathrm{CO}){:}N(\mathrm{H}_2) \sim 10^{-4}$), is used as a proxy for (tracer of) H_2[1].
  - First all-sky survey of CO in the Galaxy, and more recent update, were by Dame et al. (1987, 2001):
    `http://www.cfa.harvard.edu/mmw/MilkyWayinMolClouds.html`
    Planck Mission's updated CO map:
    `http://planck.ipac.caltech.edu/image/planck15-002c`
  - Because the typical gas/dust ratio in molecular clouds is ∼100, cold dust is another proxy for the distribution of Milky Way molecular (cloud) mass[2]:
    `http://planck.ipac.caltech.edu/image/planck15-002b`
- Relevant size & mass scales for star formation: conceptually, the Jeans radius & mass help here. For a self-gravitating cloud, one can balance kinetic & potential energy, since the latter should just "outweigh" the former for collapse to commence. The Jeans radius then falls right out[3] as

  $$R_J \sim \left(\frac{kT}{\pi(\mu m_H)^2 G n}\right)^{1/2}$$

  where T and n are the typical temperature and density of a molecular cloud. Try plugging in numbers like $T = 30$ K, $n = 10^4$ cm^{-3} and $\mu = 2$ (why?) and see what

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[1] This will be very important soon, when we discuss protoplanetary disks.

[2] This will be very important soon, when we discuss protoplanetary disks.

[3] Don't believe me on this, I am algebraically challenged...derive it.

you get for R_J. ($R_J \sim 1$ pc?)
The Jeans mass is then just

$$M_J \sim \frac{4\pi}{3} R_J^3 \mu m_H n$$

So, typical Jeans masses for the conditions above ($T = 30$ K, $n = 10^4$ cm^{-3} and $\mu = 2$) are a few $\times 10^4$ $M_\odot$. Again, don't believe me on this...plug in numbers and check.

- Some relevant timescales to ponder

  Free-fall timescale: start from gravitational force exerted on a particle of mass m at radius r within a cloud of total mass M spread over a radius R:

  $$ma(r) = -\frac{GmM(r)}{r^2}$$

  hence

  $$\frac{d^2r}{dt^2} = -\frac{GM(r)}{r^2}$$

  hence (dimensionally)

  $$-\frac{R}{t^2} \approx -\frac{GM(r)}{r^2}$$

  hence

  $$t_{ff} \approx (\frac{R^3}{GM})^{1/2}$$

  Plug in numbers for R, M: t_{ff} ~1600 s for present-day Sun; $t_{ff} \sim$ a few $\times 10^2$ for solar-mass cloud w/ $R \sim 1$ AU; $t_{ff} \sim 10^5$ yr for a solar-mass cloud the size of the Oort cloud (check me, on the last estimate!)

  Kelvin-Helmholtz timescale: During pre-main sequence evolution, stars are producing all of their luminosity via (a) release of gravitational potential energy and (b) accretion of fresh material from their disks. Mechanism (a) is governed by the K-H timescale. Start from available gravitational potential energy for a star of mass M and radius R:

  $$\Omega \approx -\frac{GM^2}{R}$$

  and then (from simple dimensional analysis) the Kelvin-Helmholtz timescale is given by

  $$t_{KH} \approx \frac{\Omega}{L_\star}$$

  For a ~1 $M_\odot$ star of a few $R_\odot$ shining at a few $L_\odot$ — see typical pre-MS evolutionary tracks (discussed later!) — the K-H timescale is a few million to tens of millions of years (again, check me!).

- The Shu et al (1987, ARAA, 25, 23) cartoon summary of the four main stages of star (and planet) formation — Fig. 7 — was long the "industry standard" for thinking about the process of protostellar collapse, disk/outflow formation (see next), and (eventually) the arrival of a newborn baby star & its planetary system: `http://www.annualreviews.org/doi/pdf/10.1146/annurev.aa.25.090187.000323` It's worth thinking about this cartoon in the context of the size, mass, and time scales just discussed.

- So, why does a *disk & outflow* system go along with star formation? The process of gravitational collapse within a molecular cloud necessarily results in formation of a central core (the eventual protostar) and a *circumstellar disk*, thanks to conservation of angular momentum. The disk is what we'll be interested in for planet formation purposes, of course — but never forget the influence of the central star! Anyway, in fact the forming star/disk system must shed an enormous amount of angular momentum and magnetic field flux if it is to form at all. An efficient means to "achieve" the angular momentum loss is via *bipolar outflows.* And, indeed, collimated outflows from young stellar objects have been not just detected but exceedingly well documented at radio through visible wavelengths for a couple decades now:
`http://www.annualreviews.org/doi/pdf/10.1146/annurev.astro.34.1.111`;
`http://www.annualreviews.org/doi/pdf/10.1146/annurev.astro.39.1.403`.
These structures can have size scales of a few tenths of a pc and dynamical timescales of hundreds of years or more (how do we know?), and are likely driven by jets that originate in the complex star-disk interaction region, where matter is accreting onto the star. And that protostellar accretion process definitely has its "ups and downs" in terms of accretion rate and (hence) outflow mass loss rate:
`https://arxiv.org/pdf/1401.3368.pdf`
But this is all for another course at another time...and notice I didn't mention the magnetic flux loss mechanism, which is an even larger can of worms...!

- The observational analog to the Shu cartoon is the Class 0/I/II/III protostar/pre-MS star classification system, which is based solely on the slopes of infrared spectral energy distributions (SEDs) plus the ratio of submm/far-IR flux to bolometric flux, in the case of Class 0. A fairly recent (observational) review/analysis of this system in the context of Spitzer and Herschel imagery & photometry is included in Dunham et al.'s (2014) review in Protostars & Planets VI:
`http://arxiv.org/pdf/1401.1809v2.pdf`

- Theoretical "pre-main sequence evolutionary tracks" — i.e., the model-predicted paths of pre-MS stars of a given mass in the H-R diagram, prior to H detonation — constitute a widely-used means to translate the age since "formation" of a (proto)star of given mass to its observable properties, i.e., photospheric temperature and luminosity. Examples of pre-MS evolutionary tracks abound in the literature; Fig. 4 in Shu et al. (1987; see above), though very old and out of date, is good for purposes of illustration of model evolutionary tracks.

- Cuts across the same pre-main sequence evolutionary tracks at a fixed time since protostar (central core) formation are called "isochrones." Here is an (ahem) excellent example of the use of isochrones to infer the ages of pre-MS stars from the recent literature:
`http://iopscience.iop.org/article/10.3847/1538-4357/aa7065/pdf`
See Figs. 4–6. Note that the axes are in this case absolute G magnitude vs. $G-K$ color, not $L_\star$ vs. T_{eff} as in the Shu figure...why? How are the two systems related? Again I digress...
- The takeaway: *This business of ascertaining the evolutionary states and ages of (young) stars is crucial in understanding the origin and early evolution of planetary systems.* More on that later!

No wait: actually, this overview of protoplanetary disks may end up being the briefest overview of anything, ever...

(1) The theoretical view of protoplanetary disk structure

- Highlights from Calvet & d'Alessio chapter in book "Physical Processes in Circumstellar Disks around Young Stars" (see their §4.1)
    - Young star (protoplanetary) disks have SEDs (due to dust emission...so watch out!) that are flatter than predicted from "standard" accretion disk theory; implies temperature falls off more slowly than $R^{-3/4}$. Why? *Irradiation by central star.*
    - Eq. 3 gives irradiation flux incident on a *flat* disk due to the central star. Note the R^{-3} dependence. This is too steep to help heat the disk at large radii.
    - BUT Eqs. 4–6 then show how the vertical structure determined assuming hydrostatic equilibrium requires that the disk (scale) height H increases with R so long as T decreases more slowly than R^{-3}:

      $$H \propto T^{1/2} R^{3/2}$$

      So the disk is *flared* and can intercept more stellar flux — thus heating can be efficient at large radii.
    - Results of "simple" calculations that take both hydrostatic equilibrium and extra stellar heating into account (see §2 of Roberge & Kamp chapter in *Exoplanets*, esp. p. 274):

      $$T \propto R^{-3/7}$$

      $$\Sigma \propto R^{-1}$$

    - Compare the latter to the R dependence of Σ for the MMSN (Roberge & Kamp chapter in *Exoplanets*, Eq. 22)
  - Highlights (i.e., figures) from a disk structure paper(s) built on such a theoretical foundation — such as Gorti et al. (2011)'s paper on modeling the multiwavelength emission line spectrum of the TW Hya disk:
    `http://iopscience.iop.org/0004-637X/735/2/90/article`
    (We will discuss Figs. 3–6)

(2) The observational view of protoplanetary disk structure & composition (plus a bit on disk evolution)

  - Run through M. Wyatt slide set on "Protoplanetary Disks" (to be available on Exoplanets course website)
  - Describe observed properties of a well-studied disk(s) — e.g., TW Hya — in some detail

Week 9: Evolution of protoplanetary disks

- DIGRESSION: how do we determine stellar ages (not to mention masses & temperatures)? Will probably briefly walk through Soderblom's (2010, ARAA) review
- Will probably present closely follow Williams & Cieza's (2011) ARAA review, "Protoplanetary Disks and Their Evolution"

Week 5: Giant planet formation

Week 6: Terrestrial planet formation