FUNDAMENTALS OF ASTROPHYSICS I (ASTP-608)
LECTURE NOTES: STARS & THE SUN
STAR FORMATION AND PRE-MS STELLAR EVOLUTION

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Star formation and pre-MS 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(CO):N(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 you get for R_J. ($R_J \sim 1$ pc?)

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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.

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 important for planet formation purposes, of course. 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 (pop quiz: how can one estimate these timescales?), 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, pulled 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...worth refreshing your memory as to how the two systems are related (we discussed this when we started into the unit on stars and stellar structure).