PHYS2160 – Lecture 4 – The Milky Way (3)

Last time

- Brief background on stars, interiors, atmospheres and evolution (main sequence, giant branches, AGB & Sne return material to the ISM)
- Luminosity, Effective Temperatures, Lifetimes. Spectral Types
- Population I and Population II

This Time

- The Interstellar Medium
- Extinction
- How the ISM collapses into stars and planets
- Stars and Planets

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The Interstellar Medium (ISM) – Shu Ch 11, ZG Ch 15

is the gas (roughly 99%) and dust (roughly 1% - condensed molecular material containing silicates, graphite, silicon carbide, polycyclic aromatic hydrocarbons, water ice …) in the space between the stars. Typical sizes range from just a few molecules up to ~1μm (much smaller than the dust in your house!)

ISM was discovered as “stationary” absorption lines in the spectra of spectroscopic binary stars (Hartmann 1904) – that is stars where the velocities of the two stellar componentises varied, but there was a third component that did not move..

Total dust mass is small, but its impact on astronomy is significant – it stops us seeing the Galactic centre in visible light, or seeing the dense regions where stars form. This is primarily because it produces Rayleigh scattering, which has an efficiency that scales as $1/\lambda$ (though there is also some actual absorption of photons, and remission at longer wavelengths as well). The impact of this iis known as extinction, and has the property that blue light is more subject to extinction than red light.

Can parameterise this as an ‘extra’ *extinction* term added into the estimation of distance.

$$m - M = 5 \log d - 5 + A_\lambda.$$

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The Interstellar Medium (ISM) – Major Components

The major components we'll concern ourselves with are the **Molecular Clouds** (the dense, cold locations where stars form), the **Cold Neutral Medium** (easily seen in our galaxy and other galaxies in radio lines at 21cm wavelengths and so a good tracer of the dynamics of galaxies), and **HII regions** (*really* easily seen in the optical and near infrared and often associated with massive star formation).

Table of Components of the ISM

Component	**Frac. Volume**	**Scale Height (pc)**	**T (K)**	**Density (cm^{-3})**	**H state**	**Primary observations**
Molecular clouds	< 1%	80	10-20	10^2—10^6	H_2	Radio and infrared molecular emission and absorption lines
Neutral Medium						
Cold (CNM)	1—5%	100—300	50-100	20—50	HI	HI 21 cm line absorption
Warm (WNM)	10—20%	300—400	6000-10000	0.2—0.5	HI	HI 21 cm line emission
Warm Ionized (WIM)	20—50%	1000	8000	0.2—0.5	HII	Hα emission and pulsar dispersion
H II regions	< 1%	70	8000	10^2—10^4	HII	Hα emission and Radio recombination lines
Coronal gas Hot Ionized Medium (HIM)	30—70%	1000-3000	10^6—10^7	10^{-4}—10^{-2}	ionized (even metals)	X-ray emission; absorption lines of highly ionized metals, primarily in the ultraviolet

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The Interstellar Medium (ISM) – Calculating Extinction

The observed flux intensity (I_{obs}) will be related to the unabsorbed flux intensity (I_{unabs}) by

$$I_{obs} = I_{unabs}\, e^{-\tau_\lambda}$$

where τ_λ is the *optical depth*, which is defined as the integral of the number density of absorbers along the line of sight, times the cross sectional area of the particles $\sigma_\lambda=\pi a^2$ and their *extinction coefficient* Q_λ. (There is a tutorial problem that will look at derivation of this exponential form).

$$\tau_\lambda = \sigma_\lambda \int_0^L n(l)\, dl = \pi\, a^2 Q_\lambda \int_0^L n(l)\, dl$$

If we have a uniform density distribution along the line of sight ($0 \rightarrow L$), (i.e. $n(l) = n$) then the integral reduces to

$$\tau_\lambda = \pi a^2 Q_\lambda\; n\, L$$

We can then relate the magnitude difference observed to the flux ratio I_{obs}/I_{unabs}

$$\Delta m = 2.5 \log\, (I_{obs}/I_{unabs}) = 2.5\log(e^{-\tau\lambda})$$

$$= 2.5 \times 0.434 \times \tau_\lambda = 1.086\, \tau_\lambda = A_\lambda.$$

We find that the optical depth (which is dimensionless) ends up having a numerically similar value to the extinction (measured in magnitudes, which is just a flux ratio and therefore also dimensionless).

The extinction, therefore tells us about the product of the path length through clouds, the space density of the absorbing particles, their cross-section, and their absorption coefficient.

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The Interstellar Medium – Nebulae

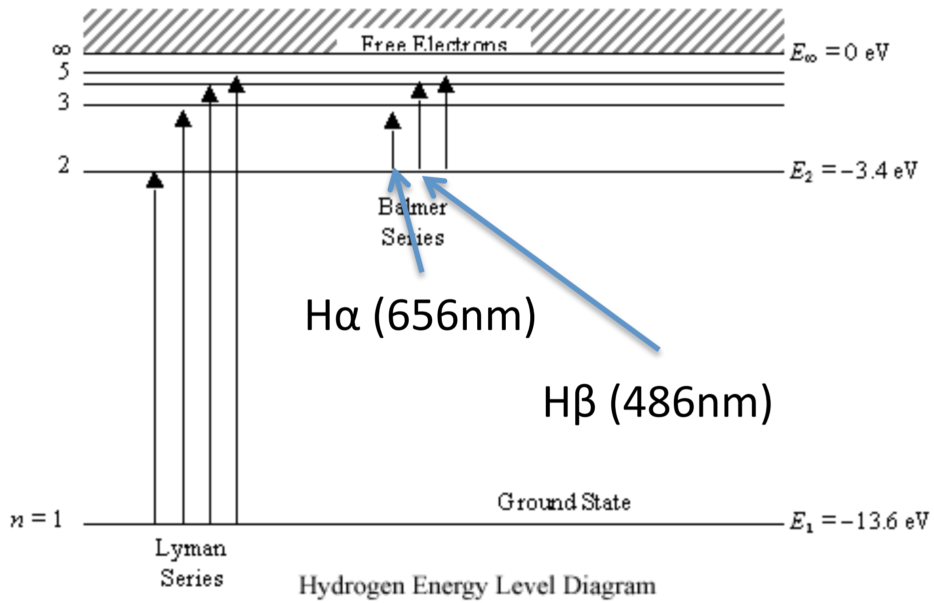
Nebulae – literally “clouds” (from the Latin). Some are seen primarily in emission, and some in absorption.

- *Dark nebulae* : opaque clouds, blocking light from behind. (e.g. Coalsack). Extinctions $A_V > 25$ (i.e. more than 10 orders of magnitude of absorption) are not uncommon
- *Reflection nebulae* : are seen in scattered light illuminated from one side. Since scattering efficiency $\propto 1/\lambda$, blue light is scattered more efficiently, so reflected light will appear to be bluish (e.g. Pleiades).
- *HII regions* : seen primarily in atomic emission lines (especially H_α at 656nm). These are typically produced when gas is photo-ionised by ultraviolet photons (i.e. E= $h\nu$ > 13.6eV or λ<91.2nm) most commonly from nearby hot O-type and B-type stars (i.e. stars with T_{eff}>20000K, which emit significant UV flux).

  When an electron and a proton recombine, the system will “cascade” down to the ground state producing a characteristic recombination spectrum.

  The “HII” refers to the nebula containing singly ionised H (“HI” means neutral H), which emits photons as electrons and protons recombine.

  The division between the ionised and neutral gas is often very sharp, at a distance from the ionising source called the Strömgren radius – as a result these regions are often known as Strömgren spheres.



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The Interstellar Medium – Nebulae – Examples

The Coalsack Nebula – a dark cloud between us and a rich field of background stars. Note there’s also a HII region in the same field … can you spot it?)

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The Interstellar Medium – Nebulae – Examples

Reflection Nebulae : The Pleiades (left) and the Ophiucus star forming region (right). Which bit of the Ophiucus image is a reflection nebula? Which is a dark nebula? What else?

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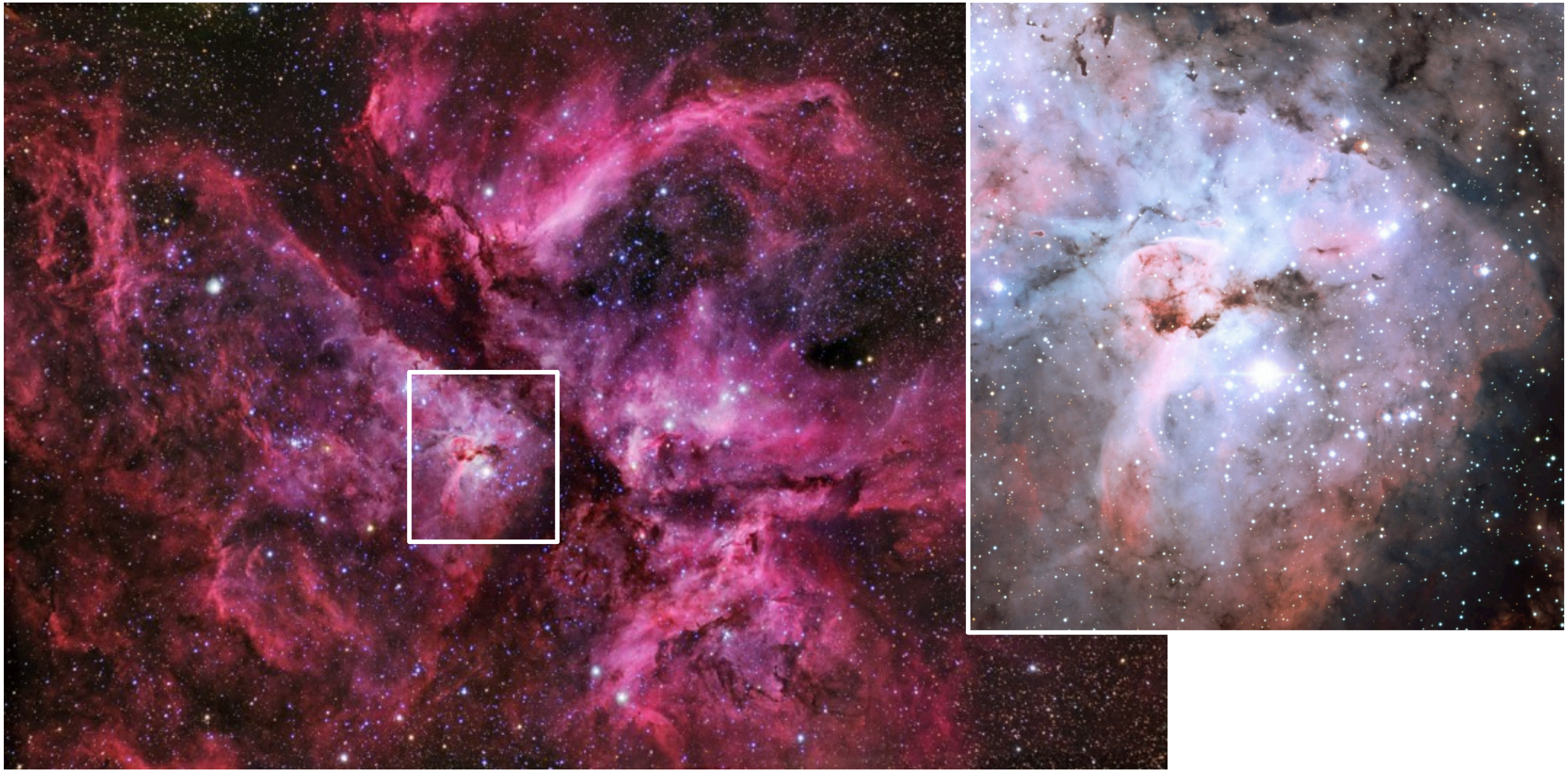
The Interstellar Medium – Nebulae – Examples

HII Regions : The Great Carina Nebula. Spot the ionising stars?



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The Interstellar Medium – Strömgren Spheres

Consider a pure H cloud of uniform density, surrounding a hot star. Let N_* be the number of photons with energy >13.6 eV (i.e. ionisation energy of H). Assume every photon ionizes one H atom. Let R by the the number of recombinations of the resulting protons (p) and electrons (e-) per unit volume per unit time.

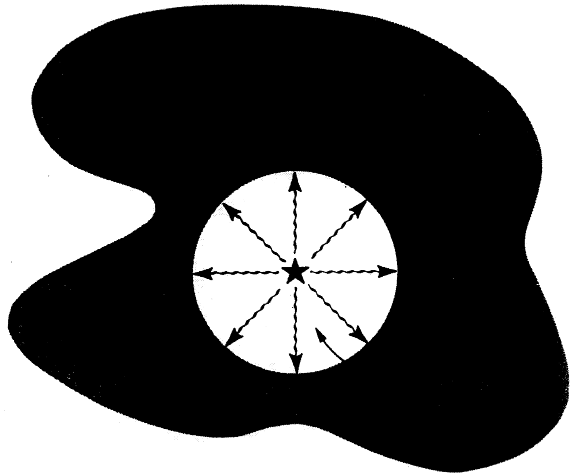

Figure 11.8. A hot and bright star embedded in a cloud of cold atomic hydrogen gas (HI) or cold molecular hydrogen gas (H_2) will ionize a roughly spherical region around itself (HII region). The size of this HII region under equilibrium conditions is given by Stromgren's requirement that the total number of recombinations occurring inside the HII region per unit time equal the total number of ionizing photons emitted per unit time by the central star.

In equilibrium, the number of recombinations and ionizations balance, so

$$4/3\pi\, r^3\, R = N_*$$

The recombination rate scales with n_p and n_e, and these densities will be equal for charge neutrality

$$R = \alpha\, n_p n_e = \alpha\, n_e^2$$

where α is the recombination coefficient (which depends on the T of the plasma). (Note that recombination here means only recombination to *excited* states of H, since recombination to the ground state just results in another ionizing photon. Recombinations to other states produce photons with e<13.6eV, and these can then escape the nebula.) The radius of the resulting ionized sphere is then

$$r = [\, 3N_* \;/\; (4\pi\alpha\, n_e^2)\,]^{1/3}$$

For a typical HII region $\alpha \approx 3\times10^{-13}\,\mathrm{cm^3/s}$, $n_e \approx 10\mathrm{cm^{-3}}$, $N_* \approx 4\times10^{46}\mathrm{s^{-1}}$ (for an O5 star), which implies $r \approx 2\mathrm{pc}$.

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The Interstellar Medium – More Nebulae

- *Planetary nebulae* : compact regions with higher gas densities excited by the UV flux from a very hot white dwarf. Gas in these higher density regions is excited by collisions between electrons, ions and atoms, resulting in substantially different spectra from HII regions.

  The shells of gas illuminated (which have arisen from mass loss as the white dwarf shed its envelope after the AGB phase as discussed last lecture) typically expand with velocities of tens of km/s

- *Supernovae remnants* : The gas ejected and swept up by supernova explosions. Gas is ejected at high speed and driven into the the interstellar medium. The resulting shock wave results in very high densities, which excite/ ionise gas to millions of K, resulting in an emission nebula. These temperatures are sufficiently hot to result in X-ray emission.

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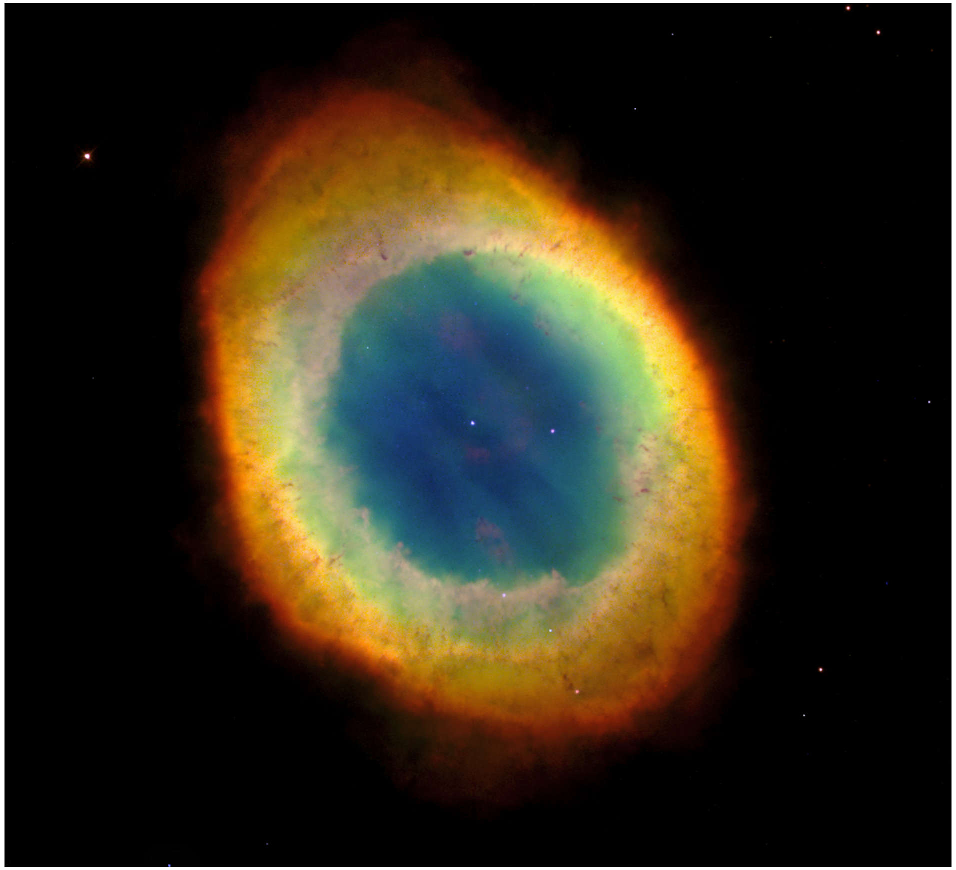
The Interstellar Medium – Nebulae – Examples

Planetary Nebulae: The Ring Nebula – a “classical” planetary (left), The Cat’s eye (HST) showing they can be much more complicated, reflecting the complex mass ejection pulses of the AGB … (right)



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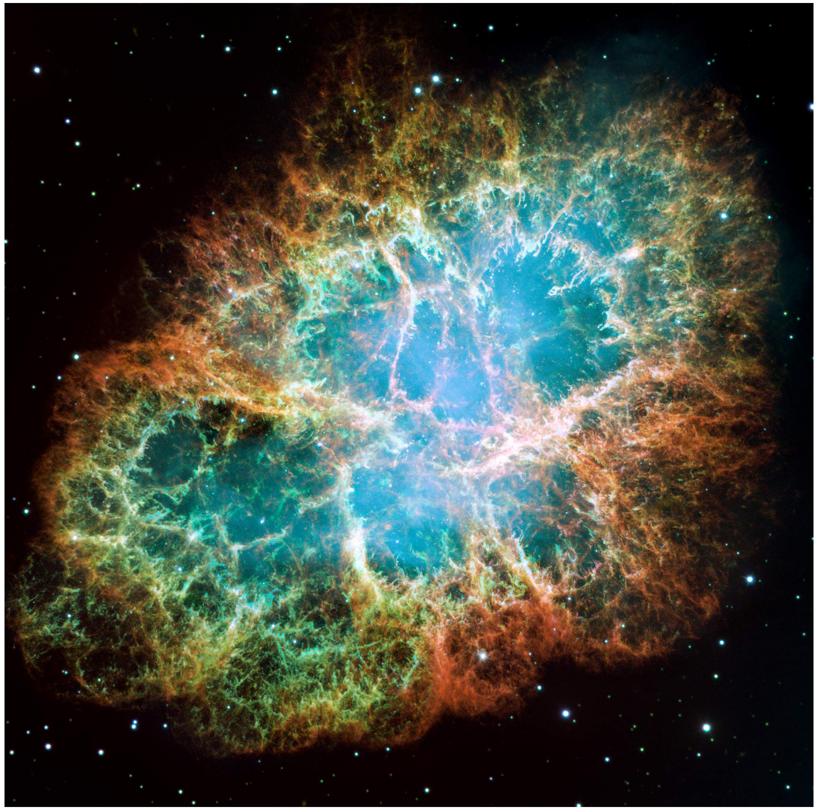
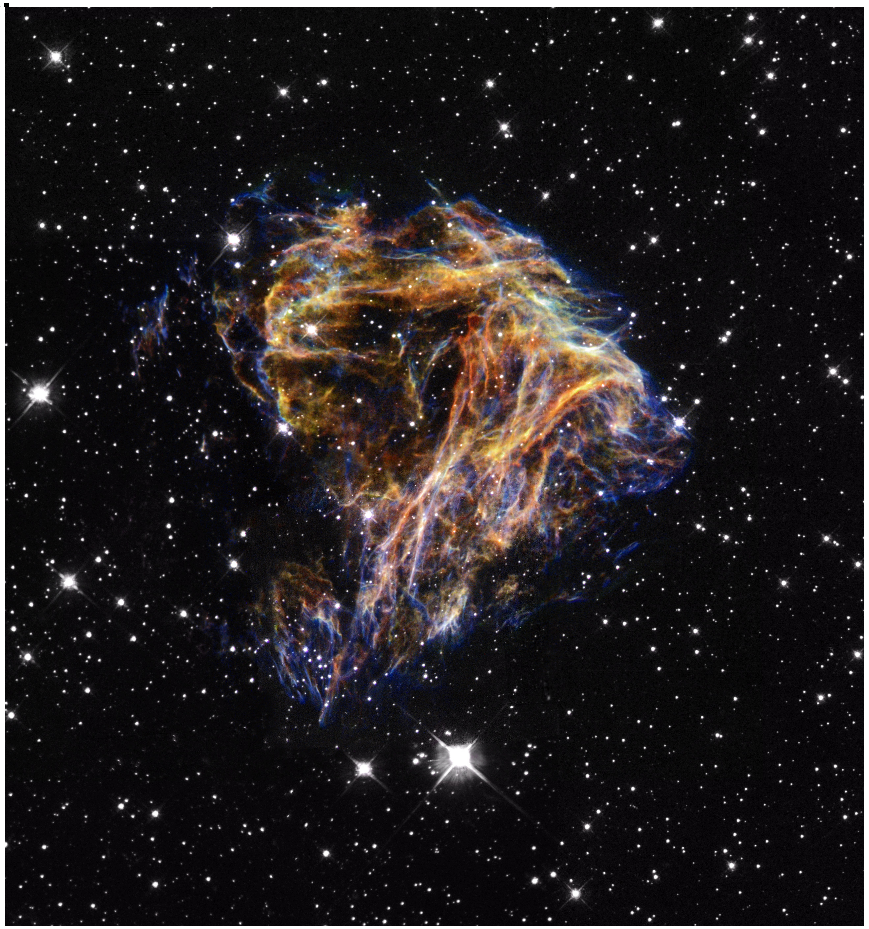
The Interstellar Medium – Nebulae – Examples

Supernova Remnants : The Crab (left) a young compact remnant from SN1054, and N49 in the Magellanic Cloud (right) an old, extended remnant.





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Star Formation – Gravitational Collapse

Stars form in molecular clouds – randomly shaped agglomerations with an essentially chaotic density distribution. Even in this densest part of the ISM (10^2-10^6 cm^{-3}) density is tiny compared to (say) the Earth's atmosphere (10^{19} cm^{-3}).

Jeans Criteria - *when does a clump of the interstellar medium become gravitationally unstable?* Consider a spherical cloud of ideal gas with radius *r*, total mass *M* and mean particle mass *m*. The cloud will have gravitational energy E_{gr}

$$E_{gr} \approx GM^2/r$$

A small radial compression of the cloud (*dr*) will produce a decrease in its gravitational energy of

$$dE_{gr} = GM^2/r^2\ dr$$

at the same time the volume will decrease by $dV = 4\pi r^2 dr$, and the thermal energy will grow by $dE_{th}=PdV$

Using the ideal gas equation PV = nkT (where n is the number of particles in the volume), we get

$$dE_{th} = nkT\ 4\pi r^2 dr = 3\ M/m\ kT\ dr/r \qquad \text{(have substituted M=volume.n.m))}$$

The cloud will be unstable to collapse if the the absolute value of the decrease in gravitational energy dE_{gr} is greater in absolute value than the increase in thermal energy dE_{th}. From this we can derive a series of **Jean's criteria** for total cloud mass, radius and density (see Tutorial Problems).

$$M_J = 3kTr/(Gm) \qquad r_J = GmM/(3kT) \qquad \rho_J = 3/(4\pi M^2)\ [3kT/(Gm)]^3$$

From this we can find that a cloud of H_2 of $1000M_\odot$ at 20K has a a Jean density of $\rho_J \approx 3\times10^{24}$ gcm^{-3} or $n(H_2) \approx 1cm^{-3}$ – if the density exceeds this, the cloud will be unstable and collapse

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Star Formation – Gravitational Collapse

$n(H_2) \approx 1\mathrm{cm}^{-3}$ is significantly less dense than the 10^2-$10^6\mathrm{cm}^{-3}$ densities mentioned earlier. Why don't all molecular clouds collapse immediately?

Real clouds are not spherical. They don't have uniform density. They have chaotically distributed density distributions and are turbulent. And they are threaded by magnetic fields.

If we consider a smaller clump (say $1M_\odot$ or 10^3 times less massive) within the cloud with the same density, then Jeans density will by 10^6 times larger.

So the 'peaks' of the density distribution (i.e. the most dense regions) will tend to collapse first.

This gravitational instability leads to the formation of protostars

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Star Formation – Protostars and Accretion Disks

The inner regions of this collapsing region will eventually form a hydrostatically supported core – a “protostar”. This will continue to accrete material, growing in mass.

But what if the material being accreted comes from a region of the ISM that has some net angular momentum? That angular momentum will be conserved. Imagine a region of collapsing material 1pc across, that has a rotation across it equivalent to a 1km/s difference. If this material collapses down under gravitational instability to being just 1au across, then the product 1pc.1km/s is conserved meaning the rotational velocity at 1au must be ~200,000km/s=0.66c!

To actually collapse to 1AU (let alone the surface of the protostar ~0.005AU) angular momentum has to be dissipated. Until that happens the materials will remain in orbit about the star. The result is the formation of an accretion disk, in which viscous and magnetic processes transport material in and angular momentum out.

Meanwhile, the central temperatures and pressures continue to rise. Above the minimum temp for H fusion (~3 million K) fusion reactions can begin and the star “turns on”.

(Below the hydrogen burning minimum mass (0.08M) this is never triggered. These objects “brown dwarfs” continually radiate energy and cool, which means they fade with time becoming both fainter and colder. Gas giant planets do the same thing of course (cool), so like brown dwarfs, their intrinsic luminosity is a function of time.)

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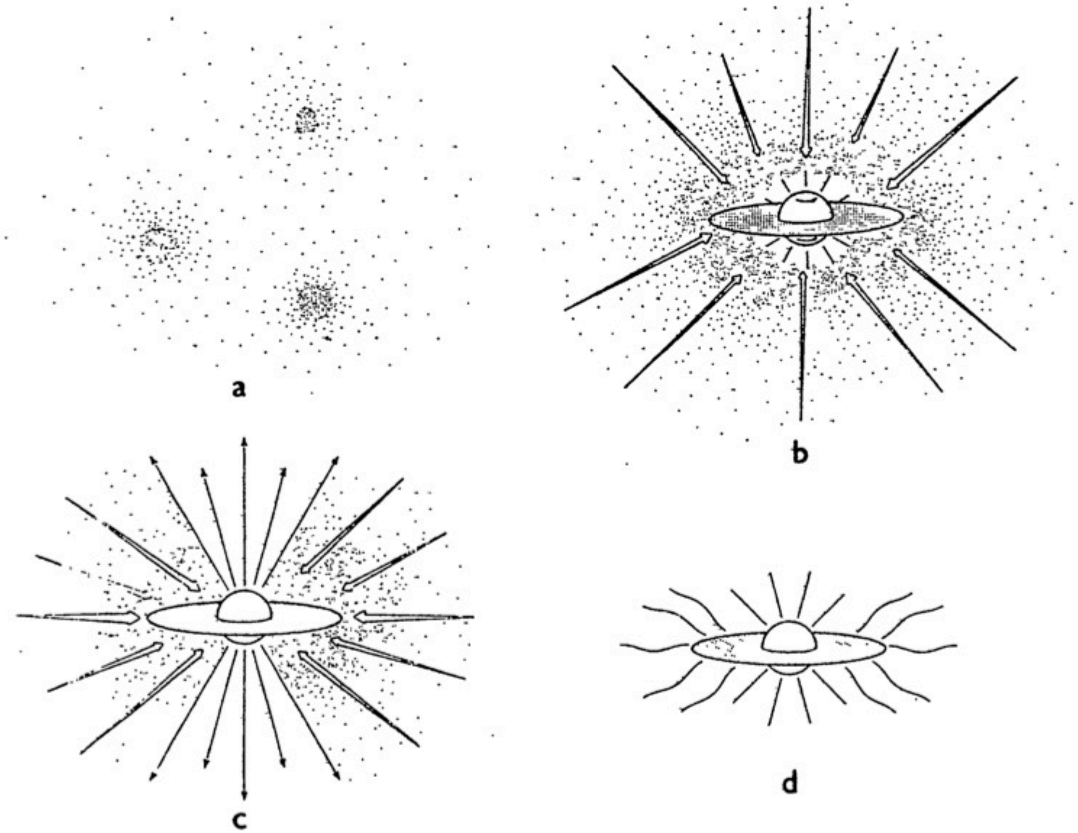

Star Formation – Protostars and Accretion Disks

The “canonical” sketch

a Globule of material in the ISM become gravitationally unstable.

b A protostar core forms, with material accreting via an accretion disk

c The accretion disk generates a polar outflow.

d Nuclear burning initiates which causes the star to dissipate the accreting material leaving only a naked disk, that eventually itself dissipates.

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Star Formation – Protostars and Accretion Disks

Detailed 3D simulations give a picture for just how complex this process is in detail. See, for example, animations by Matthew Bate, Exeter
http://www.astro.ex.ac.uk/people/mbate/Animations/

“The following calculation models the collapse and fragmentation of a 500 solar mass cloud, but resolves the opacity limit for fragmentation, discs with radii as small as 1 AU, and binary and multiple star systems. The calculation produces a cluster containing 183 stars and brown dwarfs, including 40 multiple stellar systems (i.e. binaries, triples and quadruples) to allow comparison with stellar observations.”

Animation available on the PHYS2160 Part I Materials page.


Matthew Bate, Exeter http://www.astro.ex.ac.uk/people/mbate/Animations/

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Planet Formation within Accretion Disks

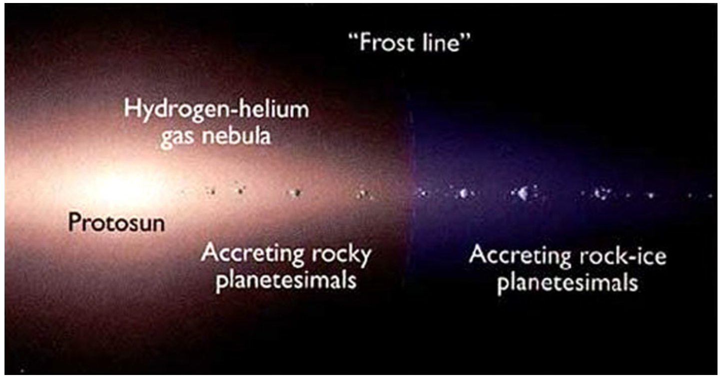
Traditional theories of planet formation seek to explain:

1. Terrestrial planets. Rocky or icy planets have composition very different from disc gas. These must have formed from collisional growth of dust or ices in the nebula.

2. Giant planets. In principle, these could form:
    1. **Via core accretion**. A core of ~10 Earth masses is formed as for terrestrial planets, then accretes an envelope of gas. (This is currently the model most likely to have produced the solar system. Exoplanet detections can be made consistent)
    2. From gravitational instabilities in the protoplanetary disc.
    3. Like stars – i.e. from fragmentation during collapse of molecular cloud cores.

Core Accretion "Stages"

1. Settling and growth of dust grains in disk
2. Pebbles and boulders to km-sized planetismals
3. Planetismals to planet-sized bodies / giant planet cores
4. Ice accretion onto giant planet cores
5. Gas accretion onto icy planet cores



The last stages suggest giant planets should only form in the *outer* regions of accretion disks beyond the "ice line" or "frost line".

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Exoplanets – How to find them

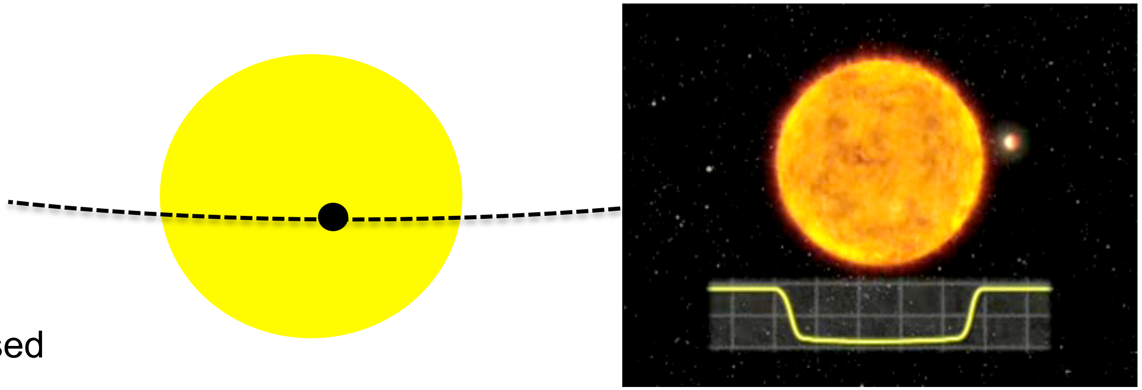
First planet around another star discovered in 1995 (51 Peg b). Now almost >1000 confirmed, and thousands more solid candidates from the Kepler satellite. Two main ways of finding them are transits and radial velocity (or "Doppler wobble")

Transits – measure relative radius of the planet and star. Very strong bias/cost against long period.

Depth ~ $(R_p/R_{star})^2=(d_p/d_{star})^2$

$R_{jupiter}$ = 71,000km => Depth ~0.01

=> Depth for Earth ~ 1 ppm !

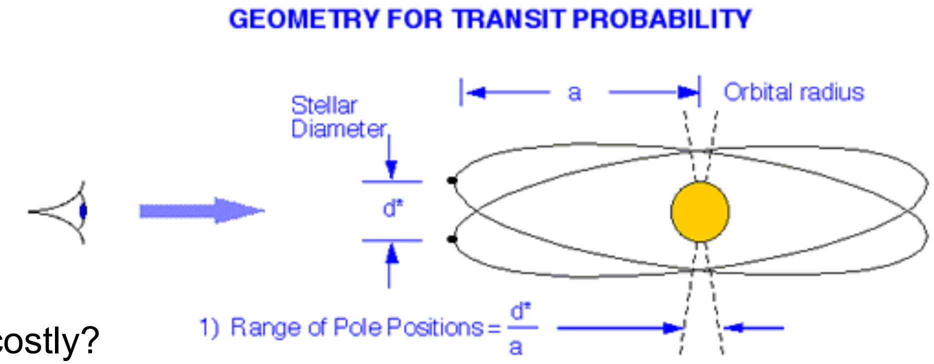


1% photometry fromground is easy, 0.1% is hard. 1ppm is impossible – you need a space-based telescope (like Kepler or COROT).

Likelihood of transit ~ d_{star}/a, but $P^2M_{star}=a^3$ (Kepler's third law) so

Likelihood ~ $d_{star}/(P^{2/3}\,M^{1/3})$

1.2% for Mercury, 0.5% for Earth, 0.09% for Jupiter



Q: Why might finding long period systems be *very* costly?

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Star Formation – Exoplanets – How to find them

Doppler Wobble – Planet and star move about barycentre of system, so unseen planet will cause star to "wobble", which can be seen as a periodic radial velocity variation. For a planet with inclination to line of sight i, mass m_2, eccentricity e, period P and orbiting star of mass m_1,

$$K_1 = \frac{2\pi \sin i}{P\sqrt{1-e^2}} \left(\frac{m_2}{m_1} \left[\frac{G\,(m_1+m_2)\,P^2}{4\pi^2} \right]^{\frac{1}{3}} \right)$$

$$= \left(\frac{2\pi G}{P} \right)^{\frac{1}{3}} \frac{m_2}{m_1} (m_1+m_2)^{\frac{1}{3}} \frac{\sin i}{\sqrt{1-e^2}}$$

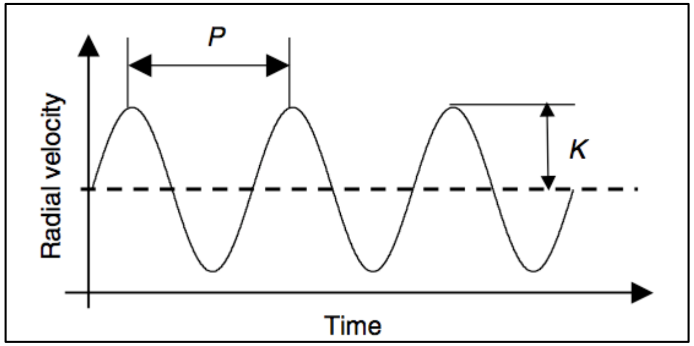

Figure 11 – Plot of radial velocity vs. time for the host star indicating how the period, P, and radial velocity semi-amplitude, K, can be determined from the data. (**Image Credit**: *Planetary Systems and the Origins of Life*, Cambridge University Press, 2007)

And if $m_2 << m_1$, (planet much smaller than star) we can further simplify to

$$K_1 = \left(\frac{2\pi G}{P} \right)^{\frac{1}{3}} \frac{m_2 \sin i}{m_1^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

Jupiter induces wobble of ~12m/s over a 12 year period in the Sun, while Earth induces ~100 mm/s. These are challenging velocity precisions to reach over long period of time.

BUT all parameters are modulo "*sin i*" term. Since an elliptical orbit always projects to an ellipse on the sky, this degeneracy can never be removed from radial velocity data alone.

Good simulator of Keplerians at http://astro.unl.edu/naap/esp/animations/radialVelocitySimulator.html

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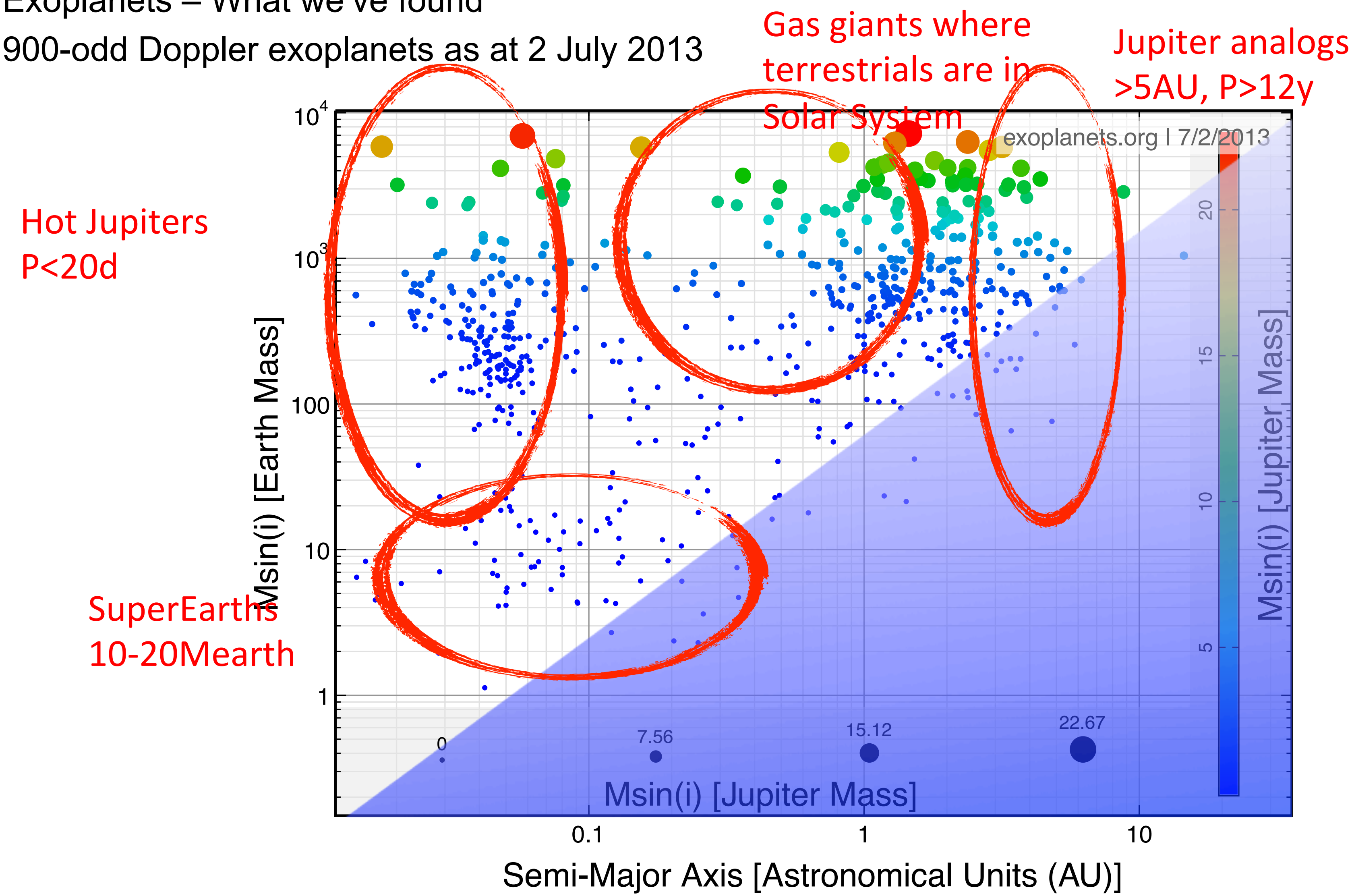
Exoplanets – What we've found

900-odd Doppler exoplanets as at 2 July 2013



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Star Formation – Exoplanets – What we find

Significant number of exoplanets are found in orbits *they shouldn't be in* under basic "core accretion" model. Gas giants inside ~2au should not be able to form there …

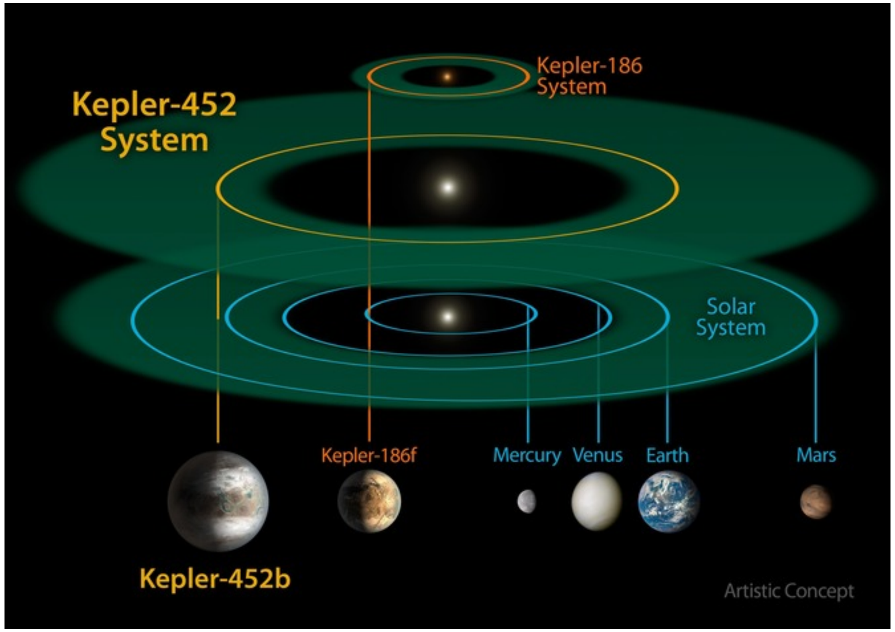
The current working solution is that they did form at larger radii, but *migrated* in to smaller radii due to interactions between the forming gas giant and the gas disk, which exert torques on the planet and so remove angular momentum and so move them to smaller radii.

Only a *very few* examples yet found of planets low enough in mass and at the right orbital separation from the host star to be habitable.

See, e.g., Kepler 22 (http://en.wikipedia.org/wiki/Kepler-22), and GJ677C (e.g. 2 Feb 2012 news item at http://www.phys.unsw.edu.au/~cgt/cgt/Homepage.html)

Or Kepler 452b announced 2 weeks ago (http://www.nasa.gov/ames/kepler/kepler-452-and-the-solar-system)

Sadly our best option for finding these systems (Kepler) failed a while ago (see e.g. https://theconversation.com/the-end-of-kepler-that-would-be-universally-bad-15953 and links therein), though it has been zombified as the K2 mission (http://keplerscience.arc.nasa.gov/K2/) , and there's more light on the horizon in the form of the NASA TESS mission (http://tess.gsfc.nasa.gov)



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- References
- Bibliography
  - Shu, F. The Physical Universe, Chapter 11
  - Zeilick & Gregory Ch 15

Useful constants, units, and formulae:

Gravitational constant	G	$=$	6.67	$\times$	10^{-11}	N m^2 kg^{-2}
Speed of light	c	$=$	3.00	$\times$	10^{8}	m s^{-1}
Planck constant	h	$=$	6.626	$\times$	10^{-34}	J s
Boltzmann constant	k	$=$	1.38	$\times$	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	$=$	5.67	$\times$	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	$=$	1.67	$\times$	10^{-27}	kg

Solar mass	$M_\odot$	$=$	1.99	$\times$	10^{30}	kg
Solar radius	$R_\odot$	$=$	6.96	$\times$	10^{8}	m
Earth mass	$M_\oplus$	$=$	5.98	$\times$	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	$=$	6.378	$\times$	10^{6}	m
Mass of moon	M_{moon}	$=$	7.3	$\times$	10^{22}	kg
Astronomical unit	AU	$=$	1.496	$\times$	10^{11}	m
Parsec	pc	$=$	3.086	$\times$	10^{16}	m
Hubble's constant	H_0	$=$	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	$=$	$5\log d - 5$ (d in pc)
Apparent magnitude	$m_2 - m_1$	$=$	$2.5\log\frac{f_1}{f_2}$
For small recession velocities	v/c	$=$	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	$=$	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	$=$	$h\nu$
Frequency and wavelength	c	$=$	$\nu\lambda$