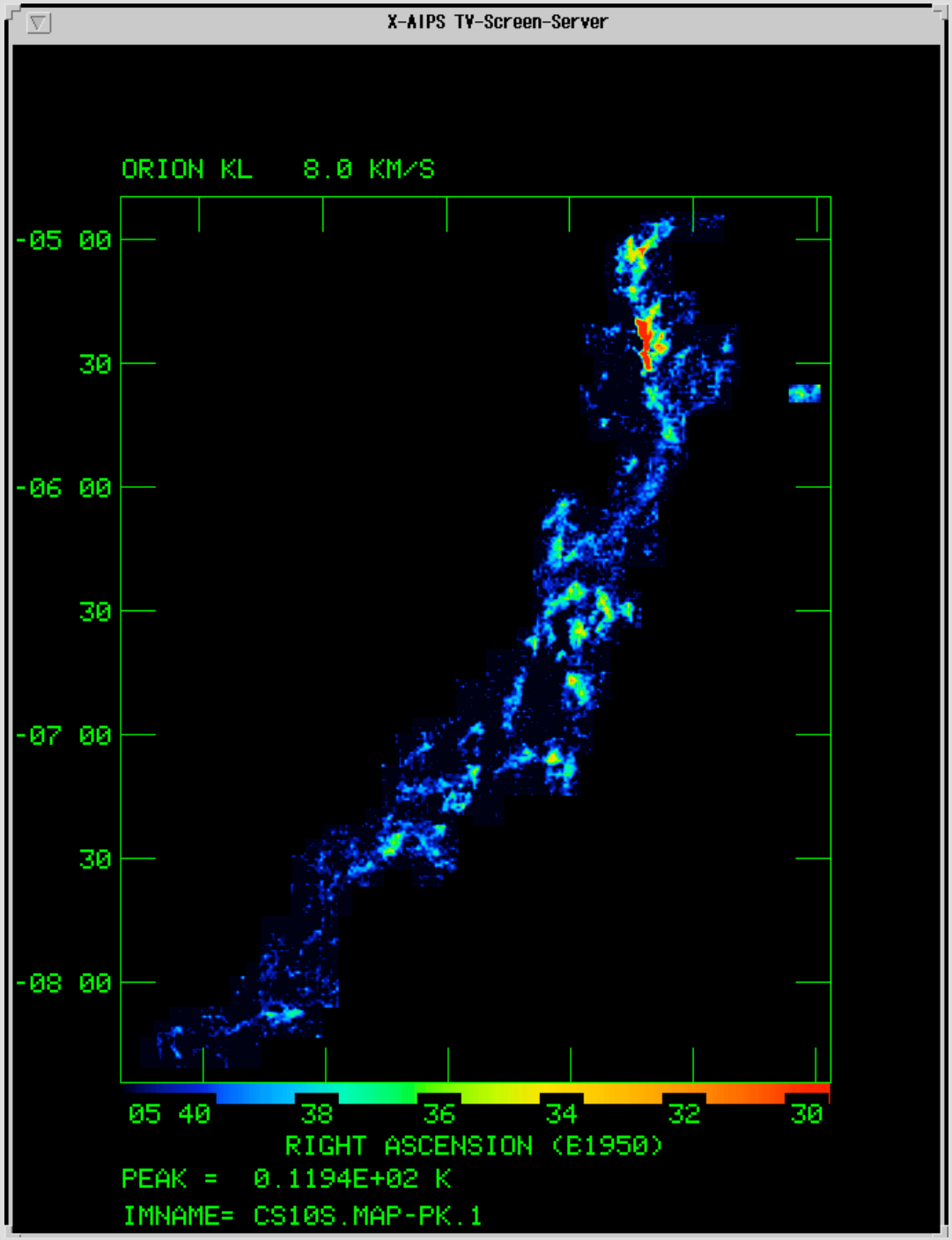
## Star formation

Stars form out of dense, cold, often dusty, molecular gas. In spiral galaxies, star formation is concentrated along spiral arms:

Hot massive stars (blue) are bizarrely shown as red in this image…

Spiral arms are places where gas is compressed, probably the first step toward star formation.




## Part of Orion molecular cloud complex

Same is true on smaller scales. Observe:

**Giant molecular clouds**

$M \sim 10^6\ M_{sun}$, $R \sim 10$ pc

→ star clusters

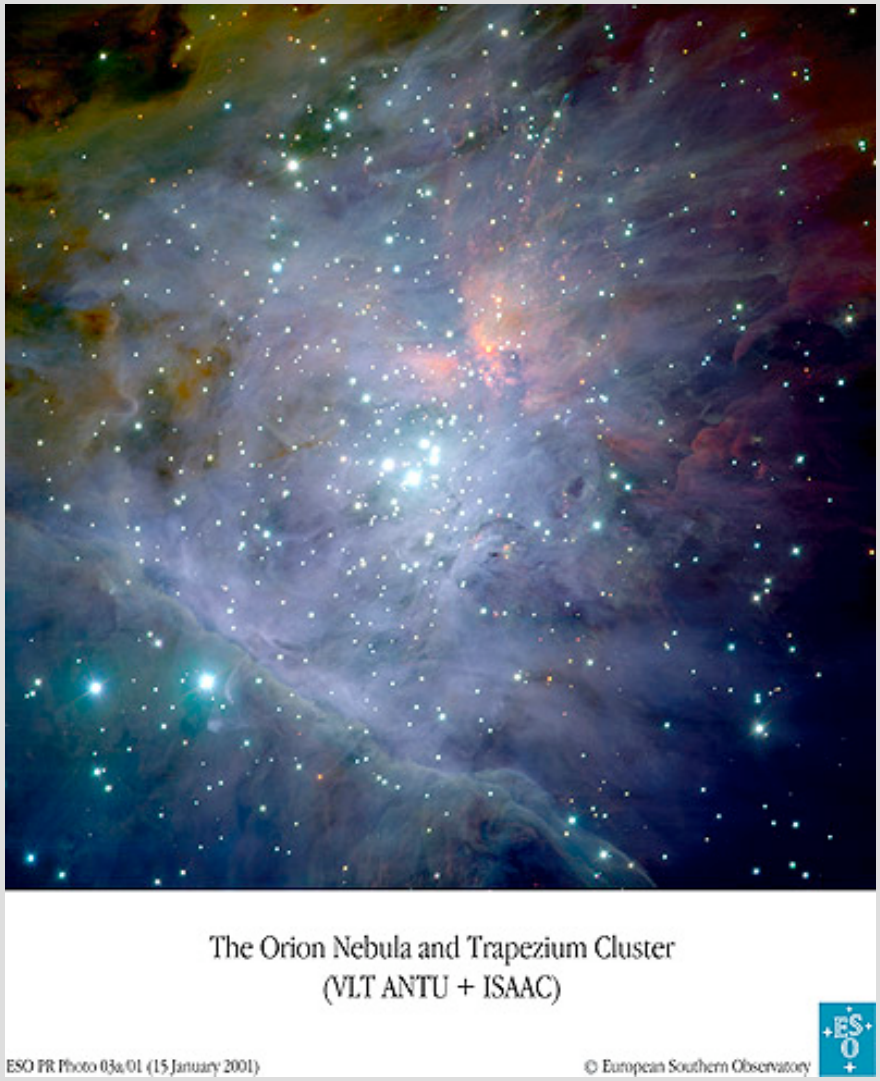
…on large scales, down to:

**Molecular cloud cores**

$M \sim$ few Solar masses
$R \sim 0.1$ pc

→ one or a few stars

Most young stars seem to have formed in clusters, ranging from relatively small groups such as Taurus to much larger clusters such as Orion:




Ionizing radiation from the massive stars in Orion provides strong feedback, and tends to blow away the gas…

Most stars today probably form in environments similar to this.

## Summary: star formation on large scales

1) Stars form out of **molecular gas** which is assembled into dense **molecular clouds** in spiral arms.

2) Molecular clouds have a complex, often filamentary structure. Individual stars, or small groups, form from the smallest scale structures, cloud cores of size ~0.1 pc.

3) Molecular clouds probably have lifetimes of $10^6$ to $10^7$ yr, which is only a few dynamical times. Star formation is a fairly rapid process once molecular clouds have formed.

4) If massive stars form within a young cluster, their ionizing radiation / stellar winds / supernovae destroy the molecular cloud on a short time scale.

5) Most stars (~80%) form in clusters at least as rich as Orion.

## Basic physics of star formation

Consider the forces acting on a `star forming unit' within a molecular cloud - a molecular cloud core:

- Gravity - act to collapse the cloud
- Pressure
- Magnetic fields
- `Bulk motions'

} sources of support against collapse to form a star

If somehow we form a core in which gravity dominates over all other forces, collapse will occur on the dynamical or free-fall time:

$$v_{esc} = \sqrt{\frac{2GM}{R}} \qquad \tau_{dyn} = \frac{R}{v_{esc}} = \sqrt{\frac{R^3}{2GM}} \sim \frac{1}{\sqrt{G\rho}}$$

…for a cloud of mass M, radius R, and mean density $\rho$.

## The Jeans Mass

Ignore for now magnetic fields and bulk motions. The *Jeans mass* is the minimum mass a cloud must have if gravity is to overwhelm pressure and initiate collapse.

Borderline case is one where the cloud is in hydrostatic equilibrium:

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho$$

To derive an estimate of the Jeans mass, consider a cloud of mass M, radius R:

- approximate derivative dP/dr by -P / R
- assume pressure is that of an ideal gas: $P = \frac{R_g}{\mu}\rho T$

…where $R_g$ is the gas constant (avoid confusion with radius)

Substitute:

$$\left(\frac{R_g}{\mu}\right)\frac{\mu T}{R} = \left(\frac{GM}{R^2}\right)$$

$$M = \frac{R_g}{\mu G} T R$$

Can eliminate R in favor of the density $\rho$ using: $M = \frac{4}{3}\pi R^3 \rho$

$$M = \frac{R_g}{\mu G} T \left(\frac{3}{4\pi}\right)^{1/3} M^{1/3} \rho^{1/3}$$

Tidy this up to get a final expression for the Jeans mass:

$$M_J = \left(\frac{R_g}{\mu G}\right)^{3/2} \left(\frac{3}{4\pi}\right)^{1/2} T^{3/2} \rho^{-1/2}$$

Basic formula for star formation. Numerical constants don't matter and vary depending on the details of the derivation.

## Mass scale of star formation

Observationally, stars form from cold dense molecular gas:

- $\rho \sim 10^{-19}$ g cm$^{-3}$
- T ~ 10 K

Use these numbers in the Jeans mass formula, and take $\mu$ = 2 for molecular hydrogen:

$$M_J = 7.6 \times 10^{32} \text{ g} \approx 0.4 M_{sun}$$

…which **matches** the typical mass of stars in the Galaxy!

Level of agreement here is `too good to be true' - however can conclude that the Jeans mass in these conditions is about a Solar mass and sets the basic mass scale for star formation.

Can likewise define a characteristic length scale (the Jeans length), by eliminating mass rather than radius from the previous expression:

$$\frac{4}{3}\pi R^3 \rho = \frac{R_g}{\mu G} T R$$

$$R_J = \left(\frac{R_g}{\mu G}\right)^{1/2} \left(\frac{3}{4\pi}\right)^{1/2} T^{1/2} \rho^{-1/2}$$

For the same density / temperature as before, $R_J = 10^4$ AU

Free-fall timescale for a cloud of this density is:

$$\tau_{dyn} \sim \frac{1}{\sqrt{G\rho}} = 10^{13}\ \mathrm{s} = 4 \times 10^5\ \mathrm{yr}$$

Conclude: star formation in these conditions ought to yield Solar mass stars within a few hundred thousand years.

What happens during the collapse?

Jeans mass formula: $M_J \quad T^{3/2} \rho^{-1/2}$

**Initially**: gas is optically thin and can cool efficiently due to radiation from molecules such as carbon monoxide

Collapse is **isothermal** during the early stages (T constant)

If T stays constant while $\rho$ increases:

- Gravity becomes even more dominant over pressure
- $M_J$ drops - allows for *possibility* that the cloud might break up into smaller fragments during the collapse itself