Dynamics of the Orion Nebula

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UNAM, Morelia, México

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Principal collaborators

CRyA-UNAM, Morelia, Mexico

- Jane Arthur
- Enrique Vázquez-Semadeni
- Sac-Nicté Serrano Medina

Elsewhere

- Fabio de Colle (UC Santa Cruz, USA)
- Garrelt Mellema (Stockholm Observatory, Sweden)
- María Teresa García-Díaz (IA-UNAM, Ensenada, Mexico)
- Bob O'Dell (Vanderbilt, USA)

Plan of the talk

What we want to explain
- Structure of the nebula
- Kinematics of ionized gas in the Orion Nebula
- Neutral gas in the heart of Orion

Physical ingredients

Building blocks for the internal dynamics

Application of H II region models to Orion

What about the stellar wind?

Large-scale structure of Orion: Herschel's view

- HYSOVAR program (Billot et al. 2012ApJ...753L..35B)
- Red: Herschel 160 µm
- Green: Herschel 70 µm
- Blue: Spitzer 8 µm + 24 µm
- Google: `herschel orion`

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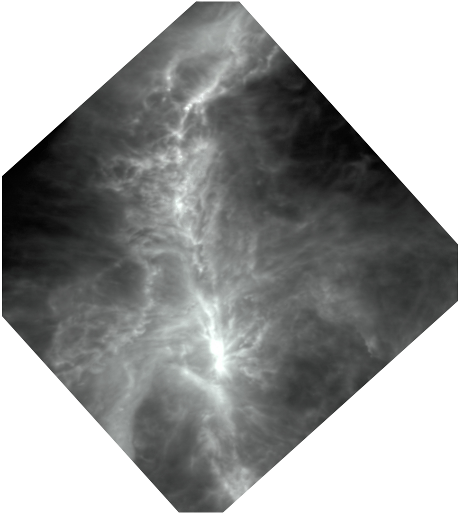

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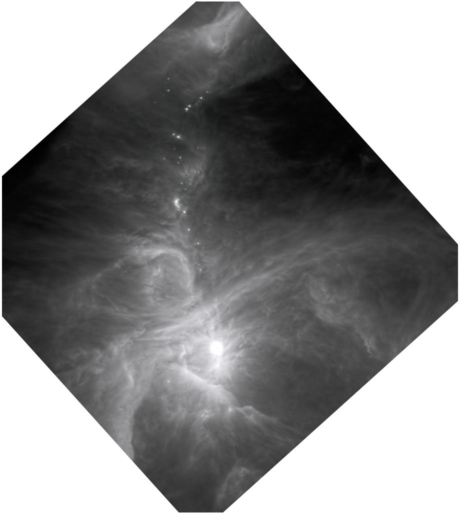

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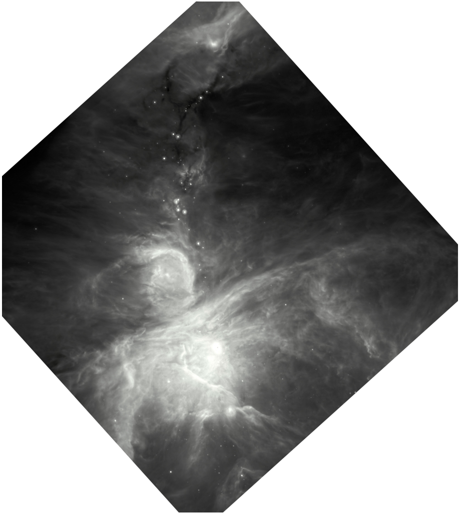

Large-scale structure of Orion: Spitzer's view

- NASA/JPL-Caltech/T. Megeath (University of Toledo, Ohio)
- Red: Spitzer MIPS 24.0 μm
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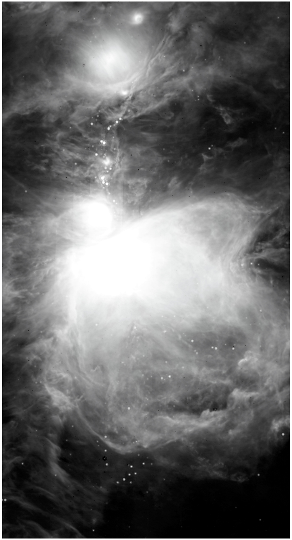

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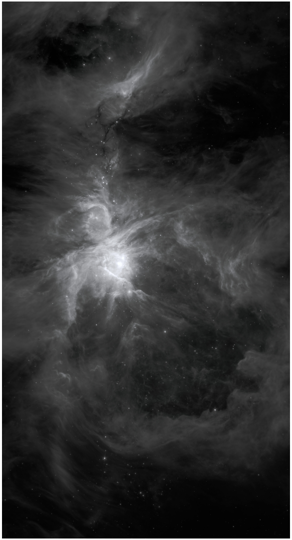

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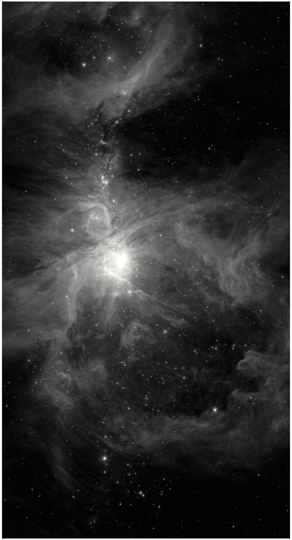

Large-scale structure of Orion: Spitzer & 2MASS

- NASA/JPL-Caltech/J. Stauffer (SSC/Caltech)
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- Blue: 2MASS 2.2 μm
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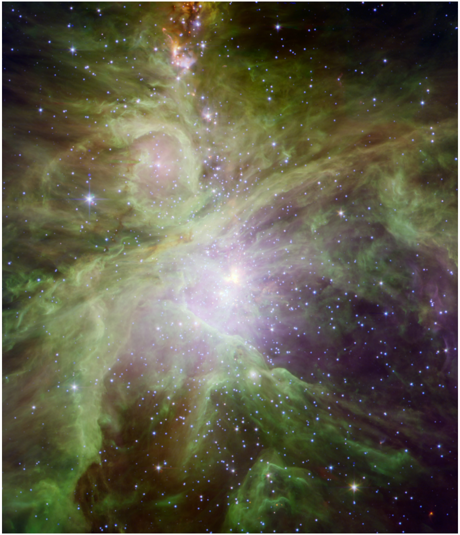

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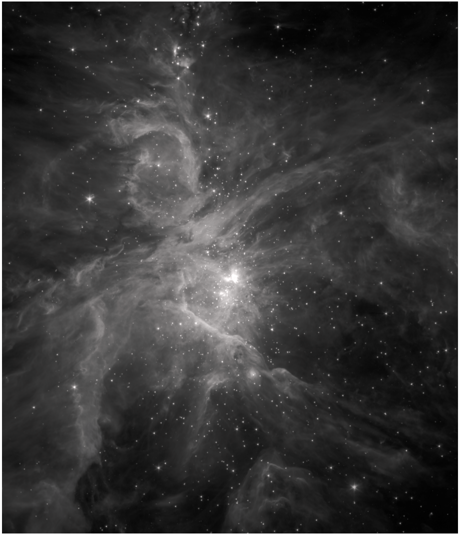

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Velocity mapping of the Orion Nebula

Lines

- [O I] 6300 Å
- [S II] 6716,31 Å
- [N II] 6584 Å
- [S III] 6312 Å
- Hα 6563 Å
- [O III] 5007 Å

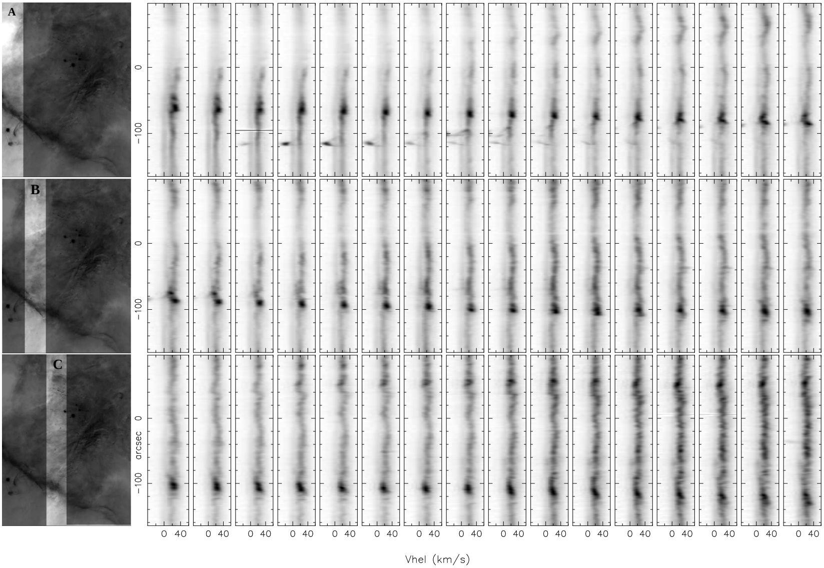
Resolution

- $3'' \times 2'' \times 10\,\mathrm{km\ s^{-1}}$

Papers

- Doi, T. and O'Dell, C. R. and Hartigan, P. (2004)
- García-Díaz, M. T. and Henney, W. J. (2007)
- García-Díaz, M. T. and Henney, W. J. and López, J. A. and Doi, T. (2008)

Longslit echelle spectra: [N II] 6584 Å



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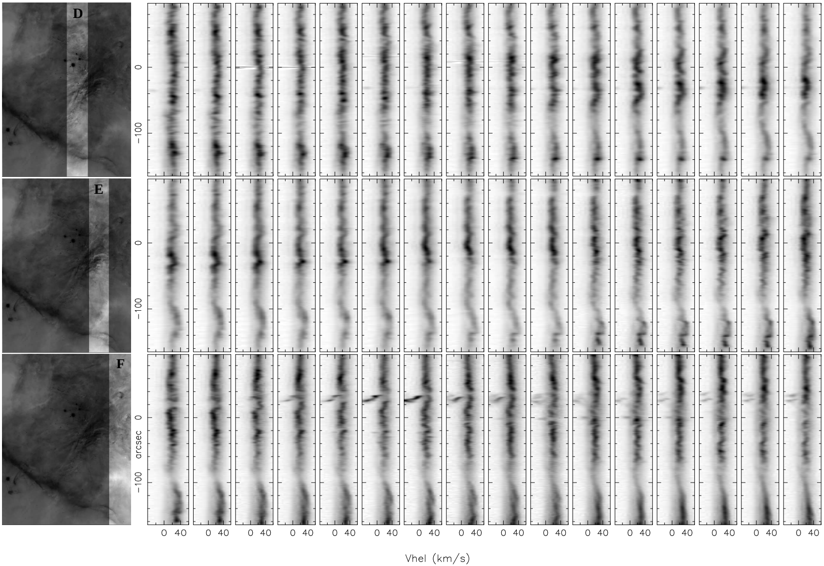
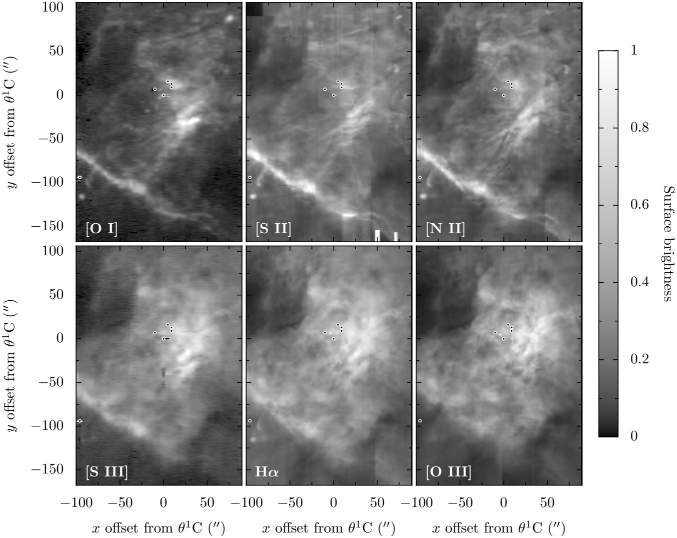
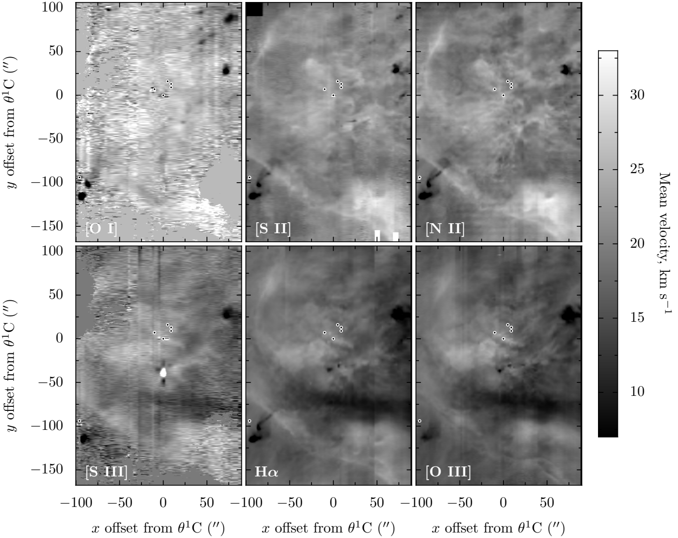


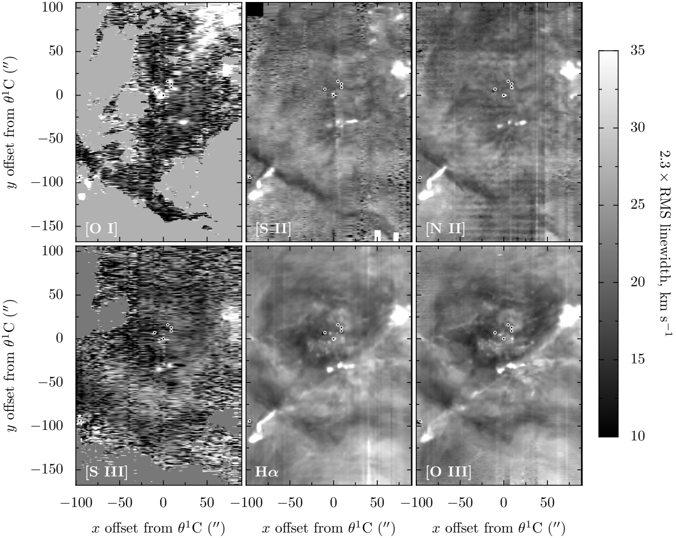
Velocity moment maps: Brightness



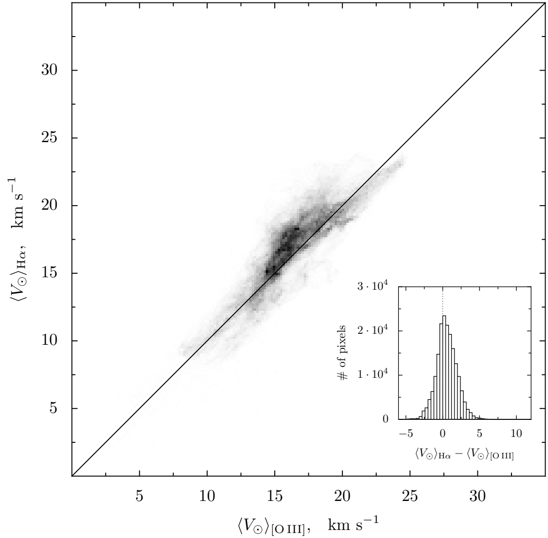
Velocity moment maps: Mean velocity



Velocity moment maps: RMS width



Velocity correlations: Hα 6563 Å versus [O III] 5007 Å



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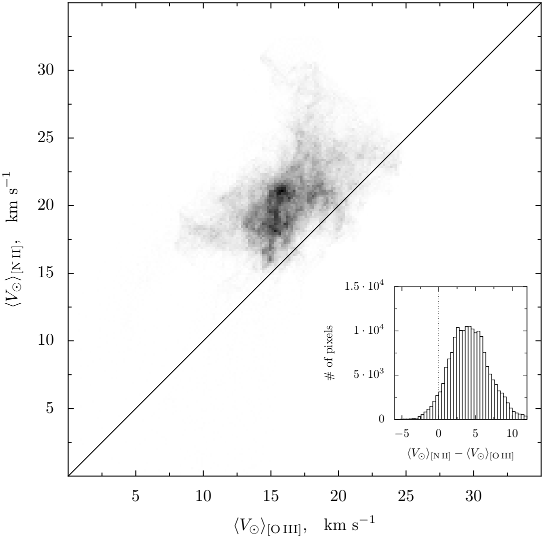
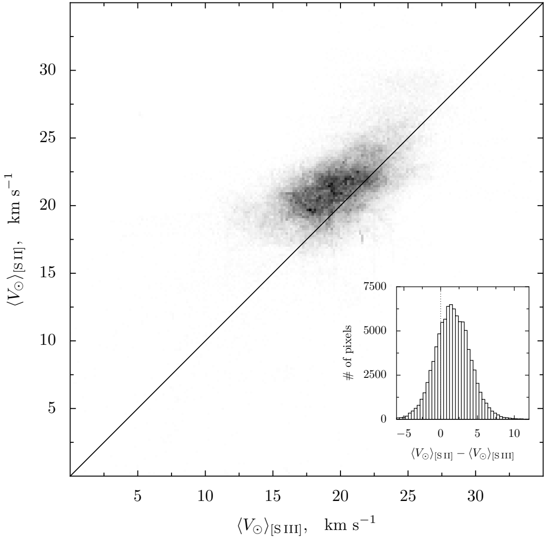
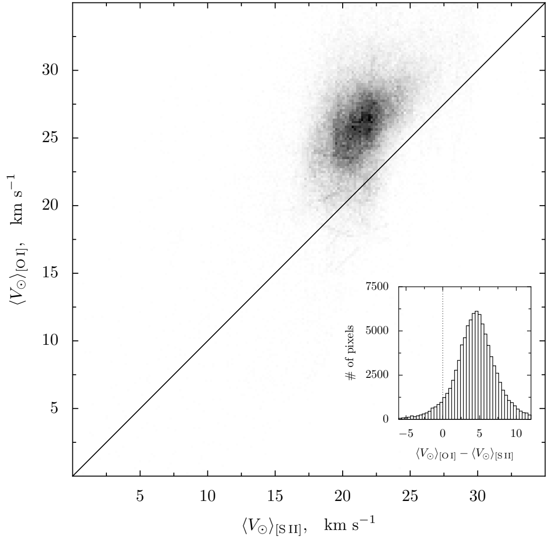


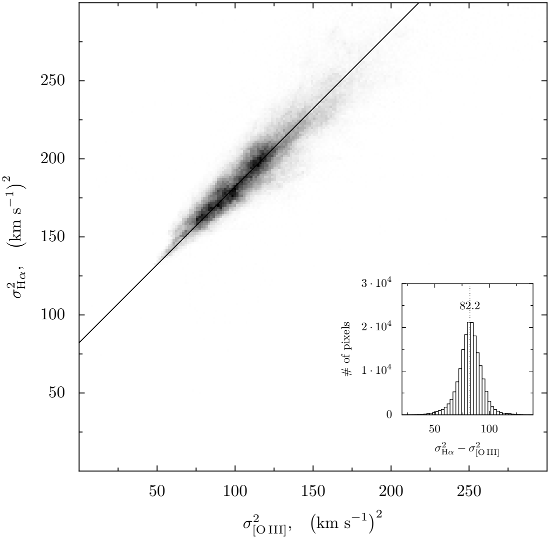
Velocity correlations: [S III] 6312 Å versus [S II] 6731 Å



Velocity correlations: [S II] 6731 Å versus [O I] 6300 Å



Linewidth correlations: Hα 6563 Å versus [O III] 5007 Å



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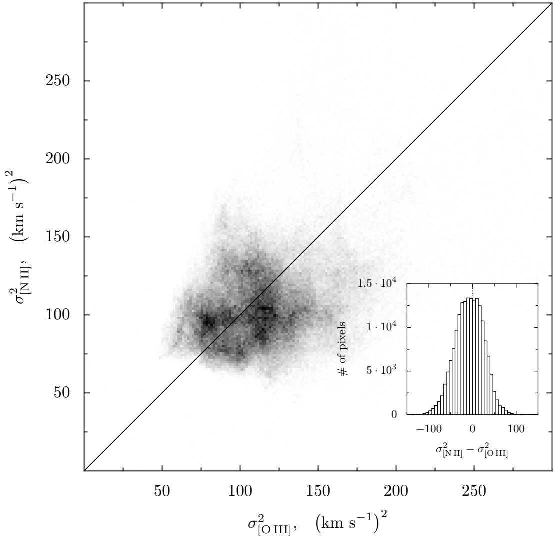

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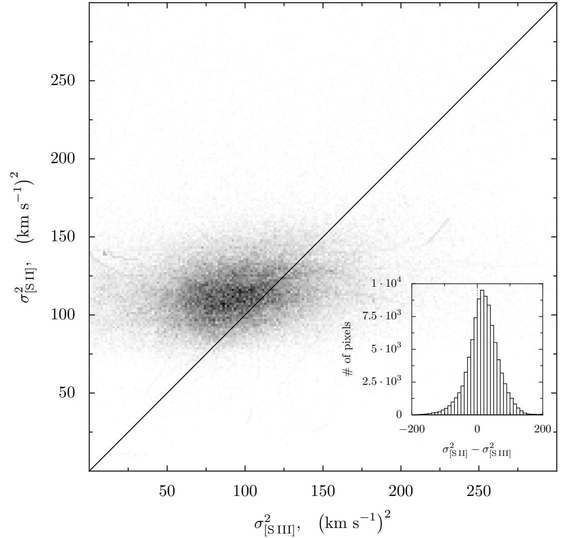

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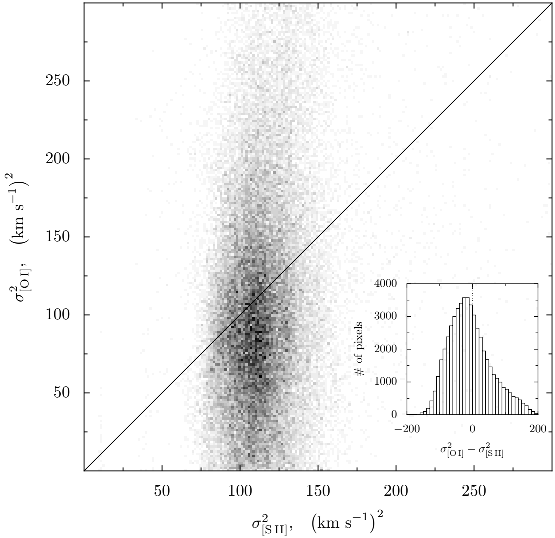
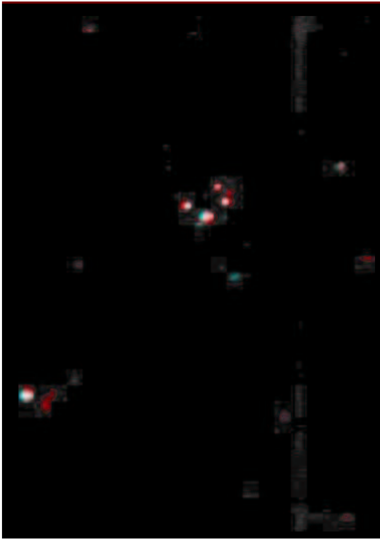
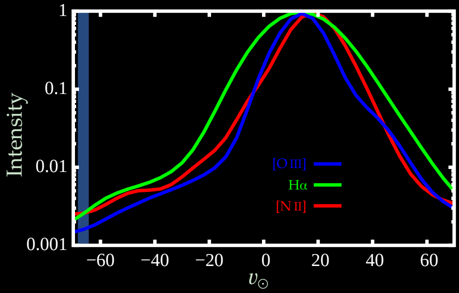


Slicing the velocity cubes





Heliocentric Velocity: −66.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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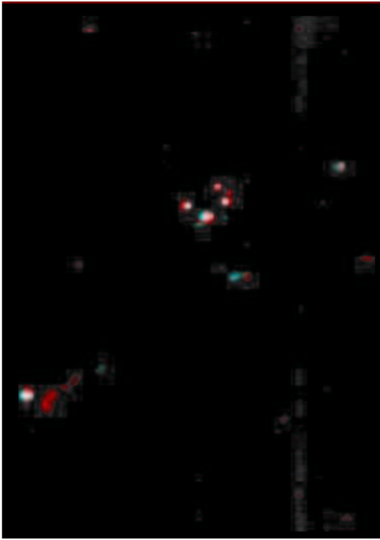
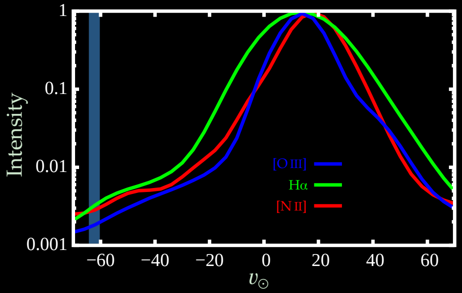
Slicing the velocity cubes





Heliocentric Velocity: −62.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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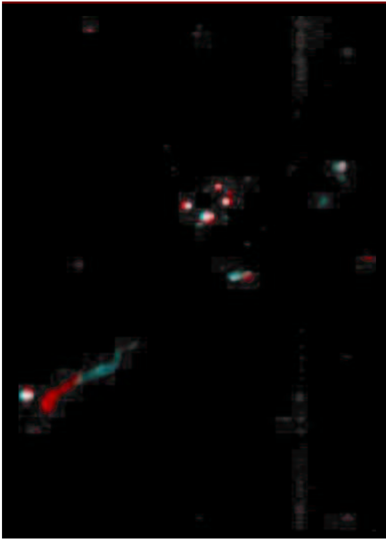
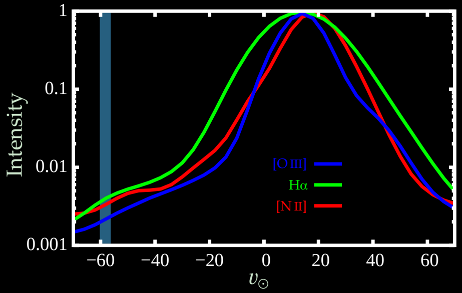
Slicing the velocity cubes





Heliocentric Velocity: −58.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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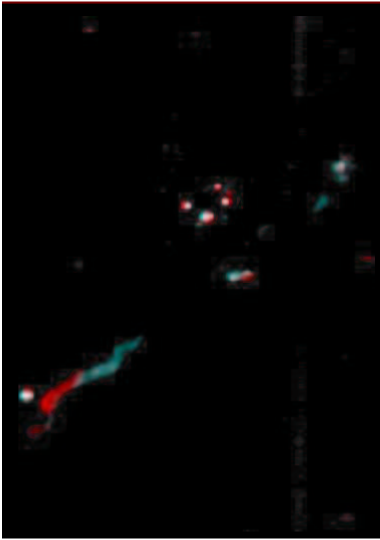
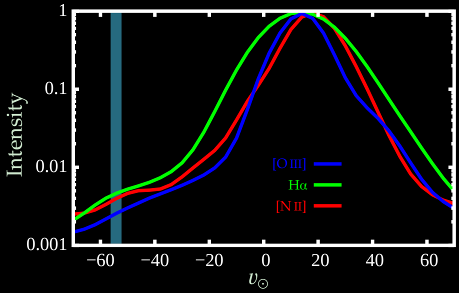
Slicing the velocity cubes





Heliocentric Velocity: −54.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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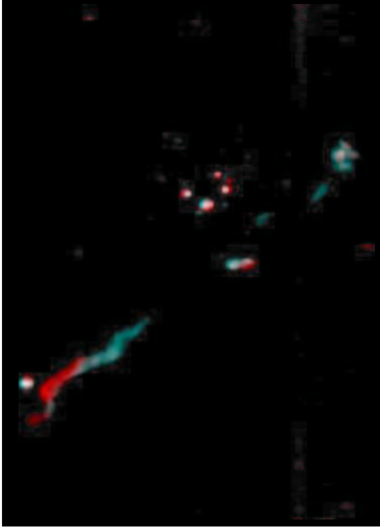
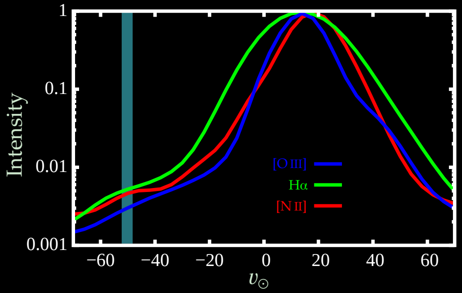
Slicing the velocity cubes





Heliocentric Velocity: -50.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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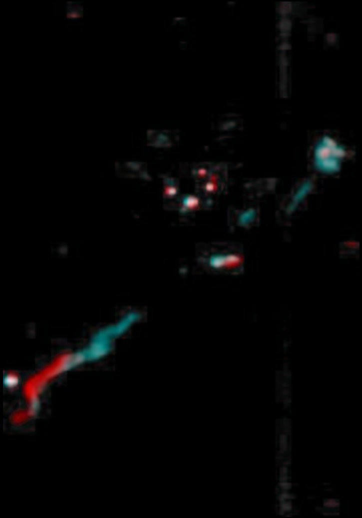
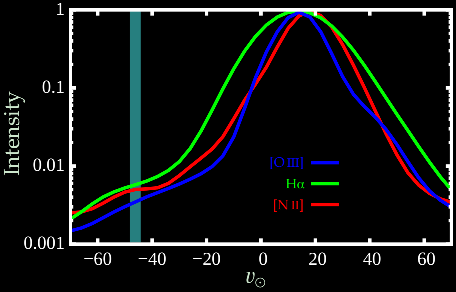
Slicing the velocity cubes





Heliocentric Velocity: −46.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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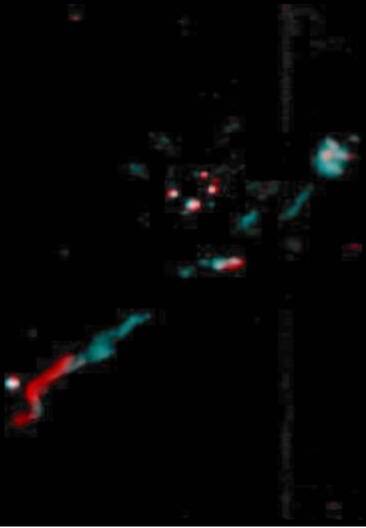
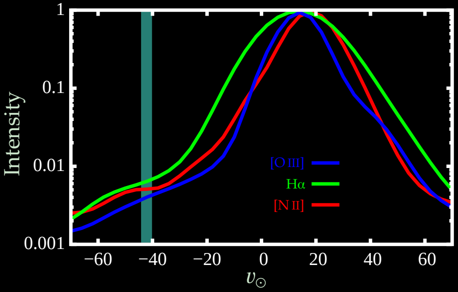
Slicing the velocity cubes





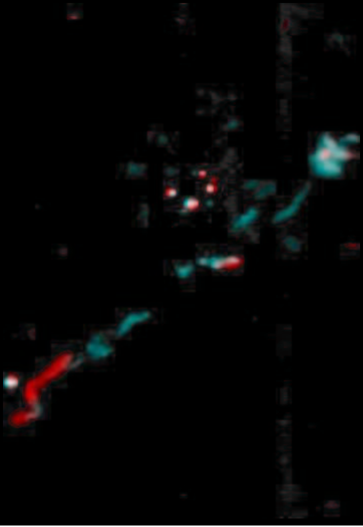
Heliocentric Velocity: −42.0 km/s

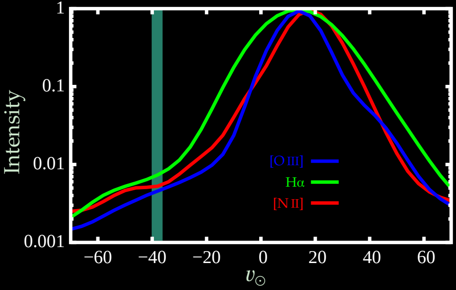
Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

Slicing the velocity cubes





Heliocentric Velocity: −38.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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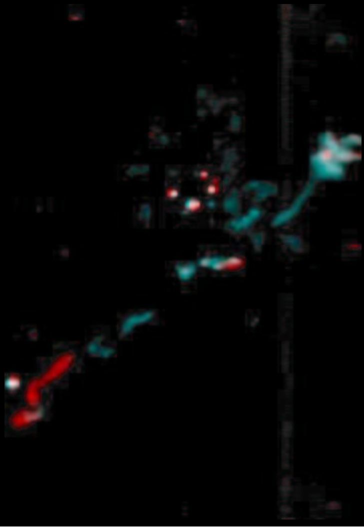
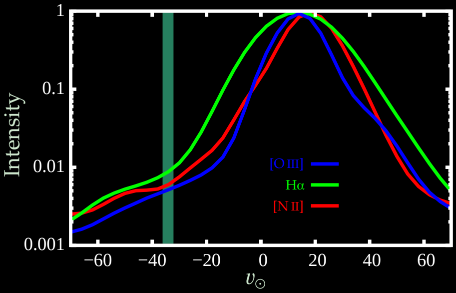
Slicing the velocity cubes





Heliocentric Velocity: −34.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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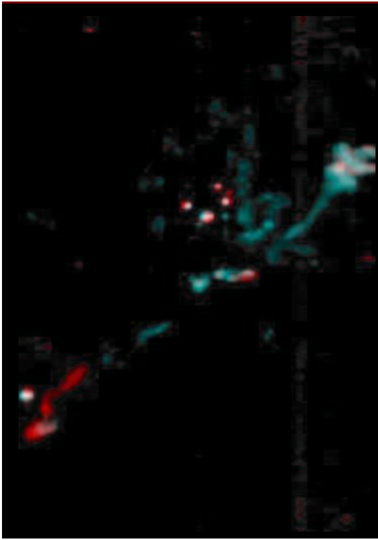
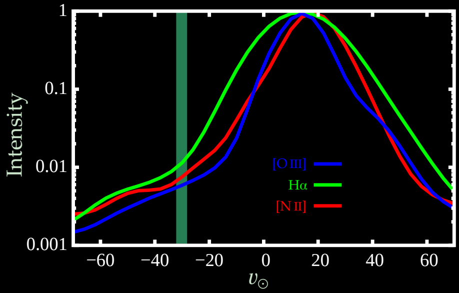
Slicing the velocity cubes





Heliocentric Velocity: −30.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O’Dell, Ferland, & Henney 2000; Doi, O’Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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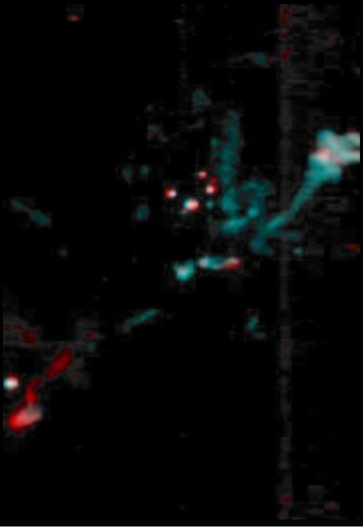
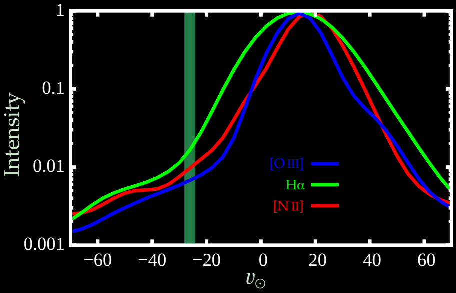
Slicing the velocity cubes





Heliocentric Velocity: −26.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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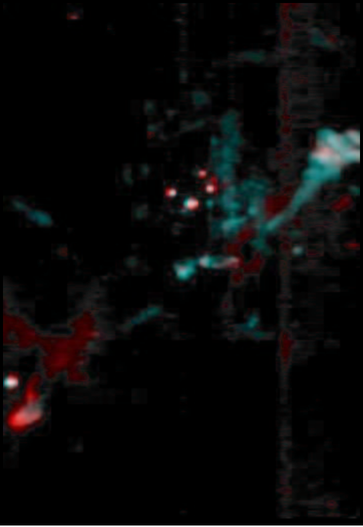
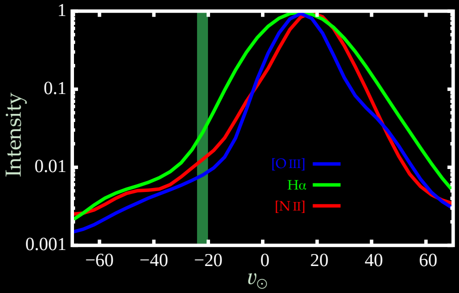
Slicing the velocity cubes





Heliocentric Velocity: −22.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O’Dell, Ferland, & Henney 2000; Doi, O’Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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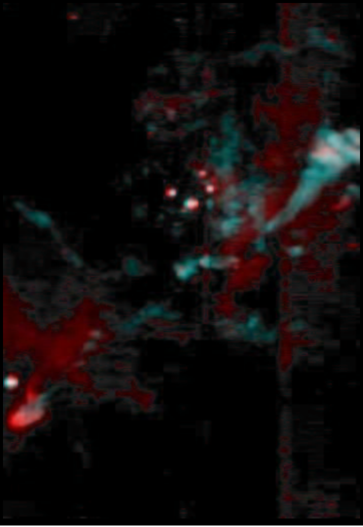
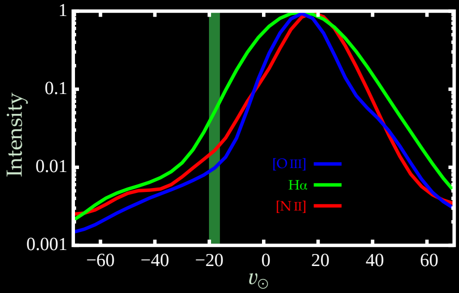
Slicing the velocity cubes





Heliocentric Velocity: −18.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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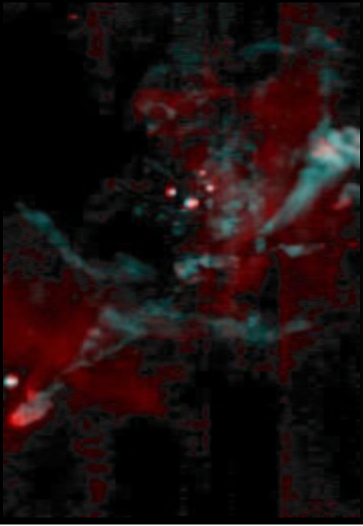
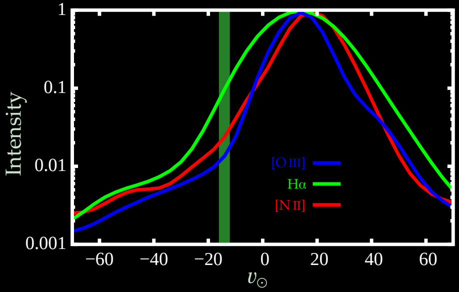
Slicing the velocity cubes





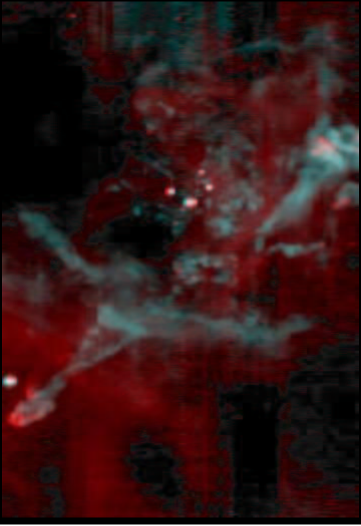
Heliocentric Velocity: −14.0 km/s

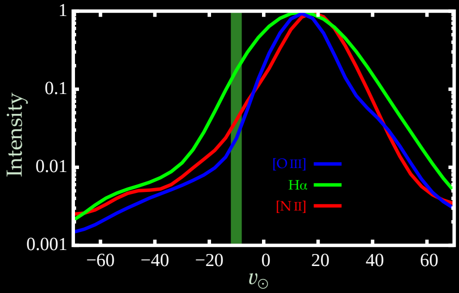
Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

Slicing the velocity cubes





Heliocentric Velocity: −10.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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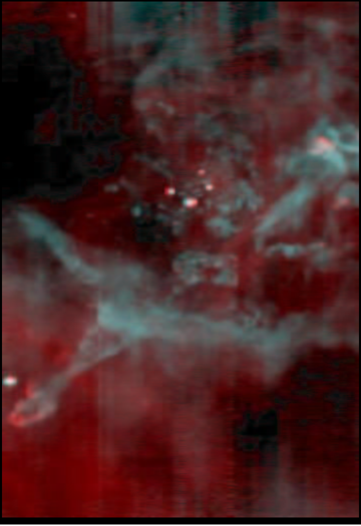
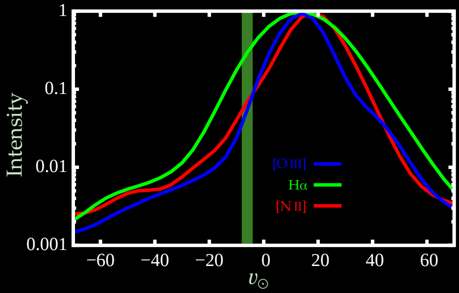
Slicing the velocity cubes





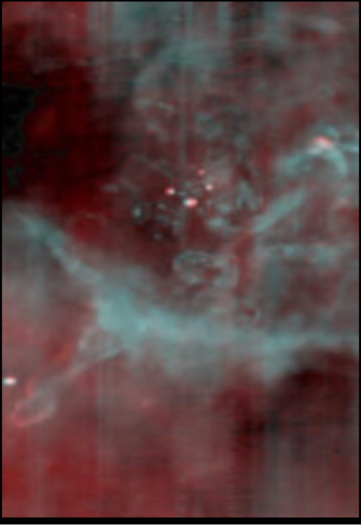
Heliocentric Velocity: −6.0 km/s

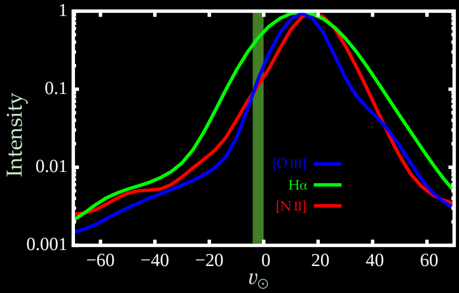
Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

Slicing the velocity cubes





Heliocentric Velocity: −2.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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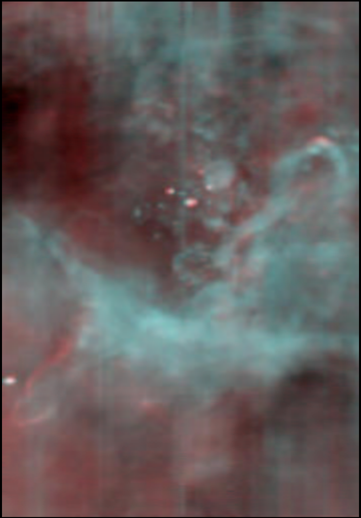
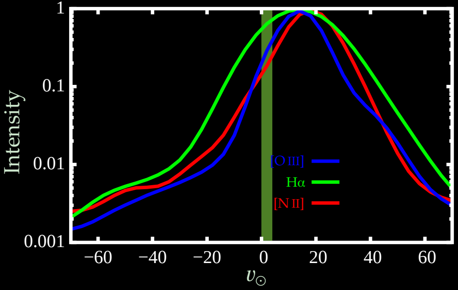
Slicing the velocity cubes





Heliocentric Velocity: 2.0 km / s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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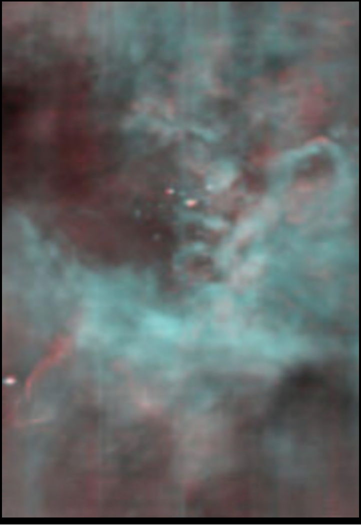
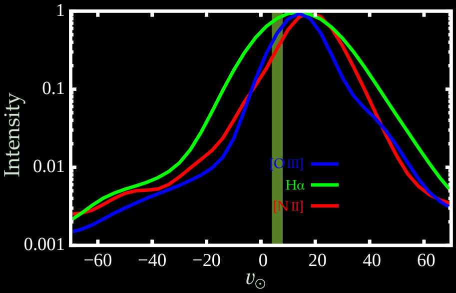
Slicing the velocity cubes





Heliocentric Velocity: 6.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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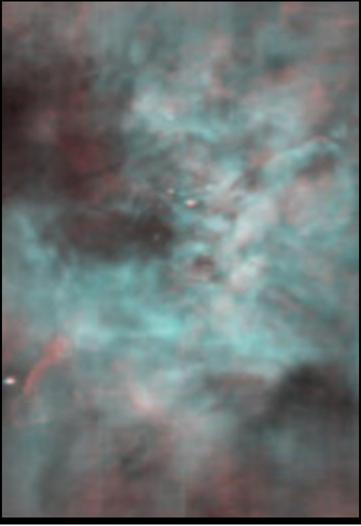
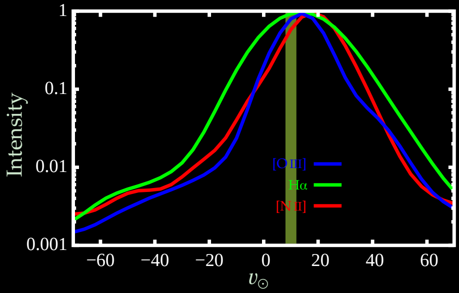
Slicing the velocity cubes





Heliocentric Velocity: 10.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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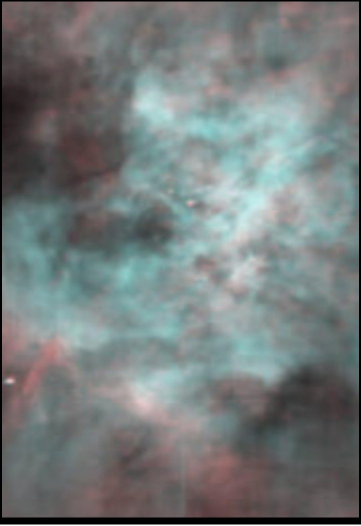
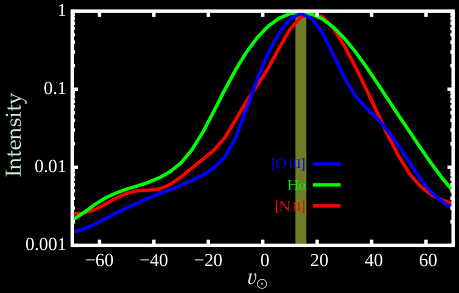
Slicing the velocity cubes





Heliocentric Velocity: 14.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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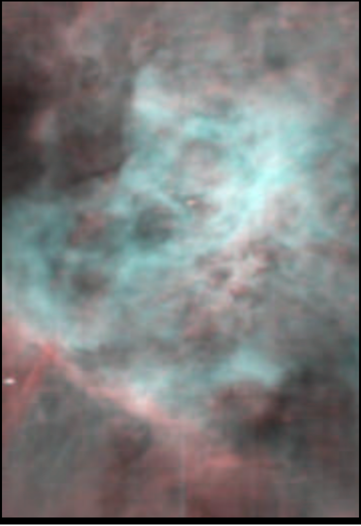
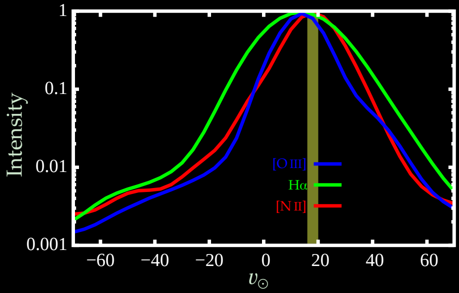
Slicing the velocity cubes





Heliocentric Velocity: 18.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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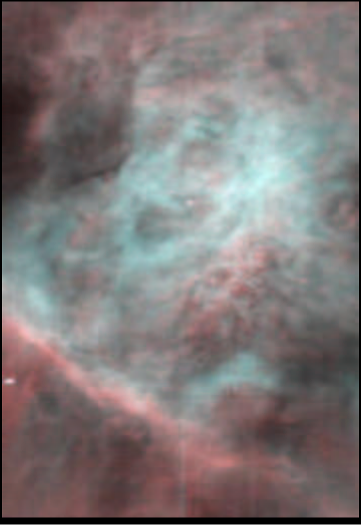
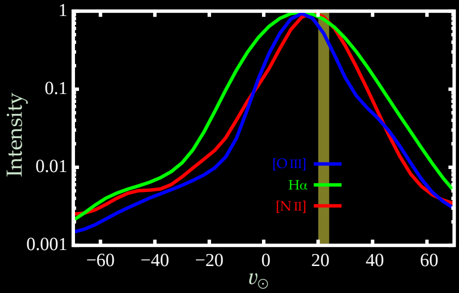
Slicing the velocity cubes





Heliocentric Velocity: 22.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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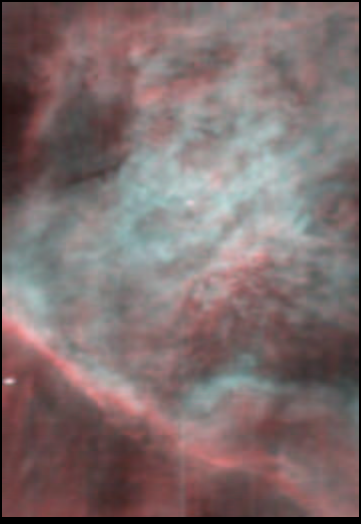
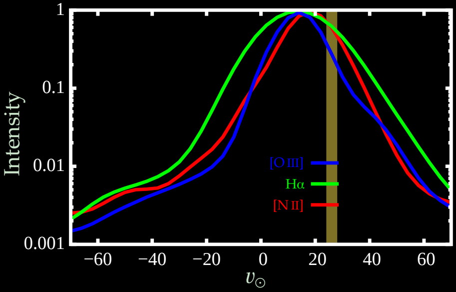
Slicing the velocity cubes





Heliocentric Velocity: 26.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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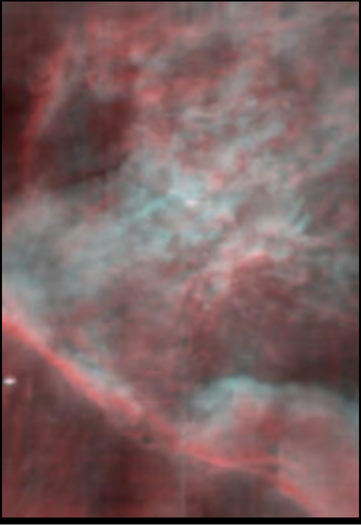
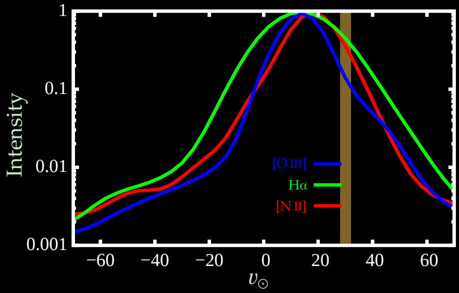
Slicing the velocity cubes





Heliocentric Velocity: 30.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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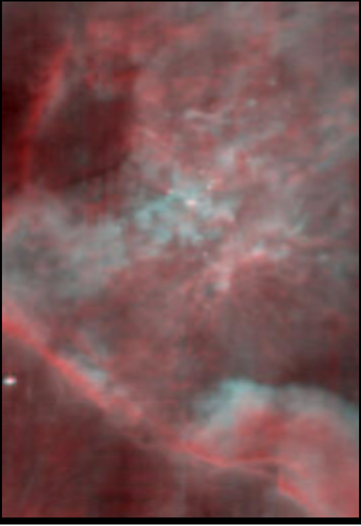
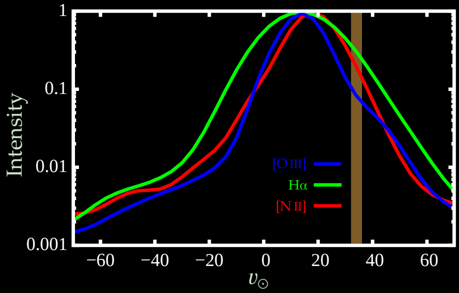
Slicing the velocity cubes





Heliocentric Velocity: 34.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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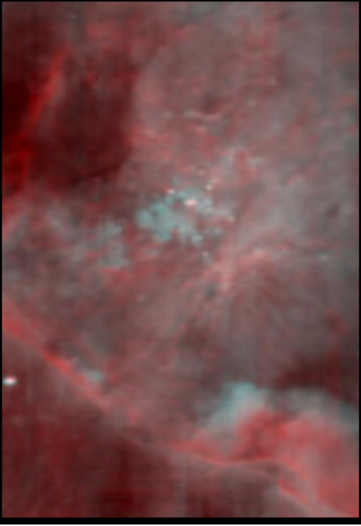
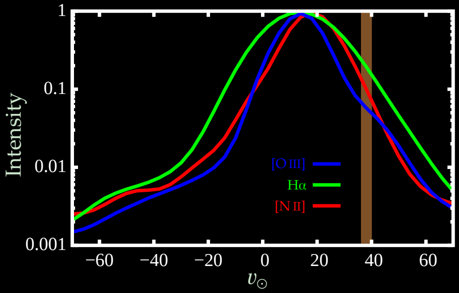
Slicing the velocity cubes





Heliocentric Velocity: 38.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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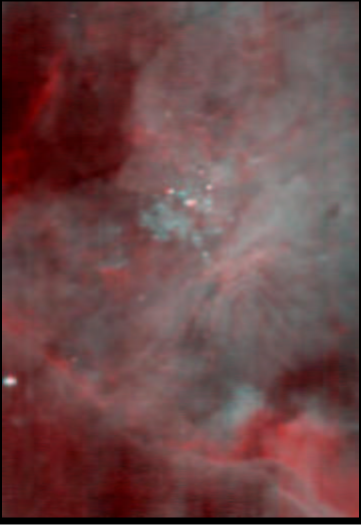
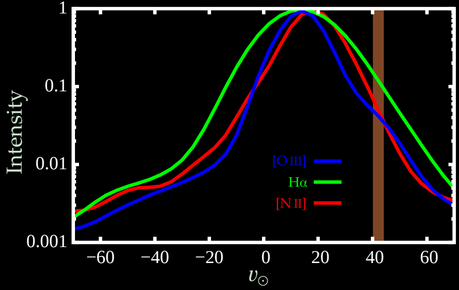
Slicing the velocity cubes





Heliocentric Velocity: 42.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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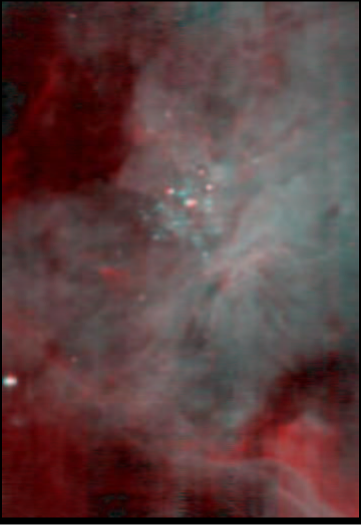
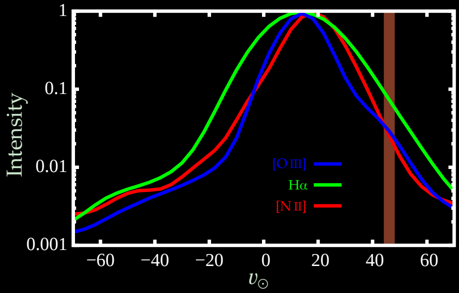
Slicing the velocity cubes





Heliocentric Velocity: 46.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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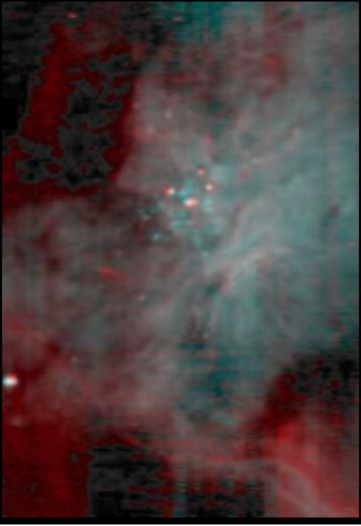
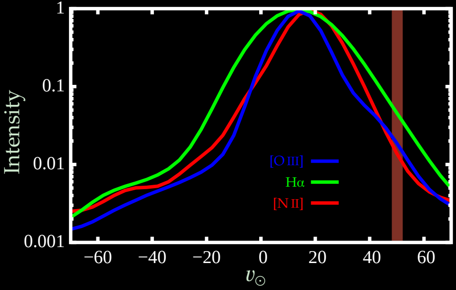
Slicing the velocity cubes





Heliocentric Velocity: 50.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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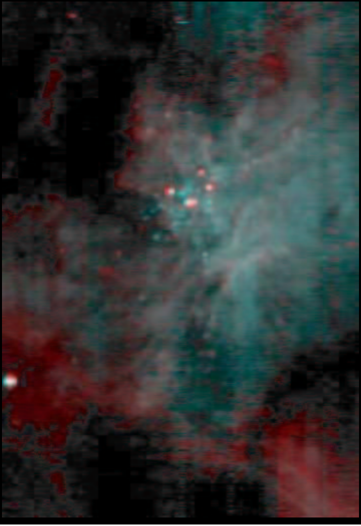
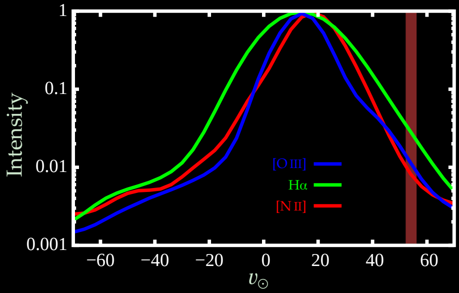
Slicing the velocity cubes





Heliocentric Velocity: 54.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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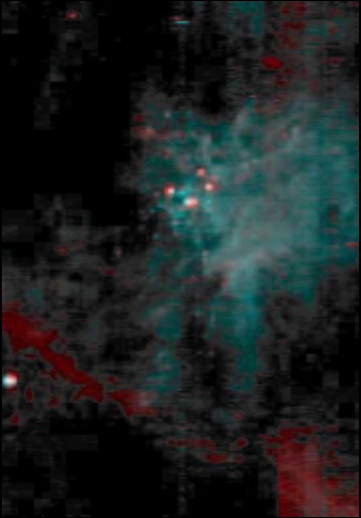
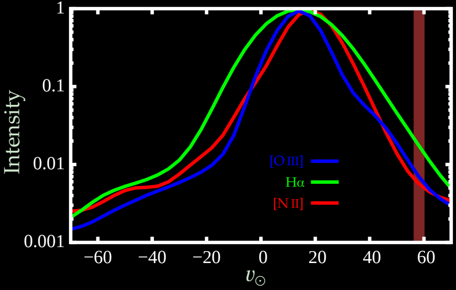
Slicing the velocity cubes





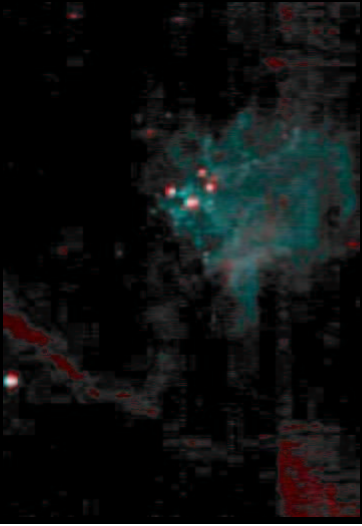
Heliocentric Velocity: 58.0 km/s

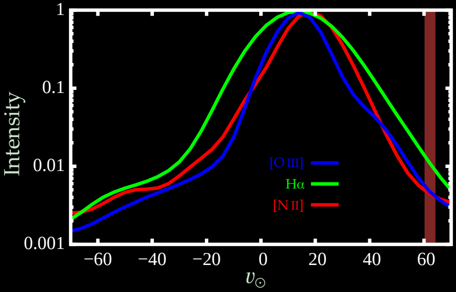
Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O’Dell, Ferland, & Henney 2000; Doi, O’Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

Slicing the velocity cubes





Heliocentric Velocity: 62.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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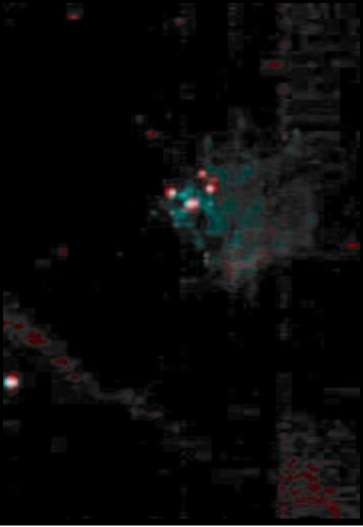
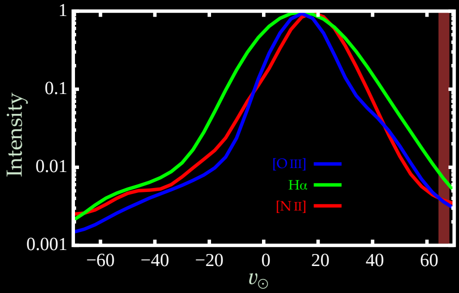
Slicing the velocity cubes





Heliocentric Velocity: 66.0 km/s

Velocity cube reconstructed from 96 N-S slit pointings, separated by 2″

[O'Dell, Ferland, & Henney 2000; Doi, O'Dell, & Hartigan 2004]

[García-Díaz & Henney 2005]

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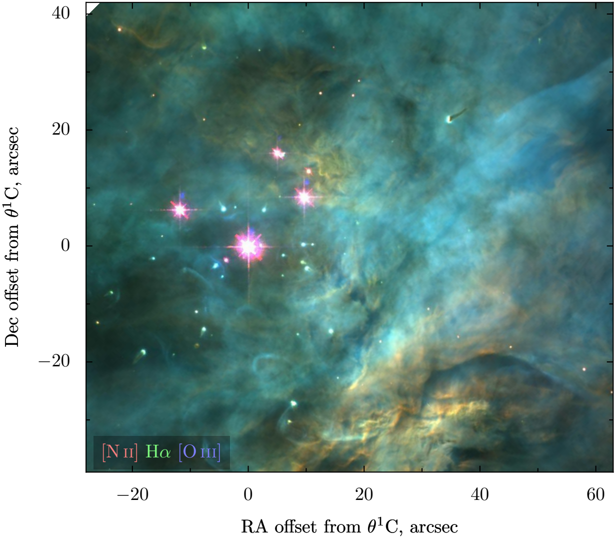
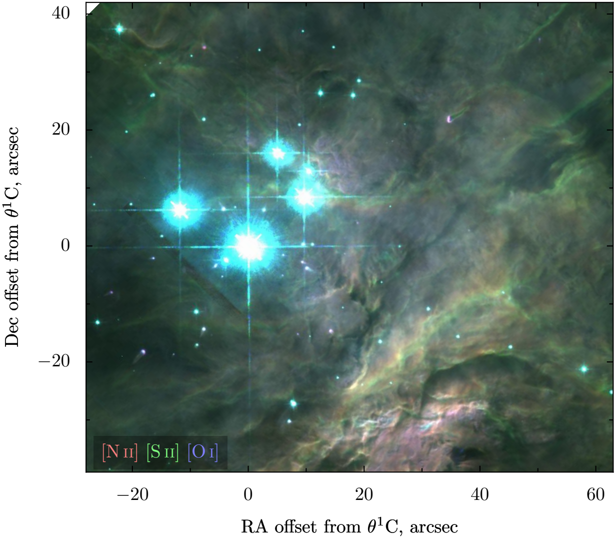
Zooming in on the Trapezium region

Zooming in on the Trapezium region

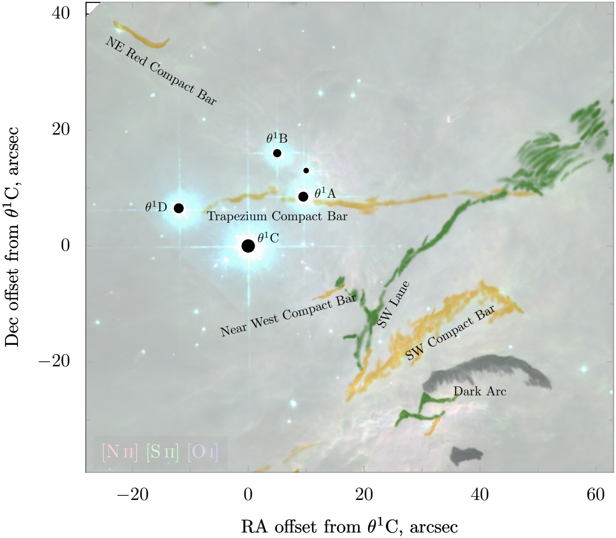
Bright bars and dark lanes



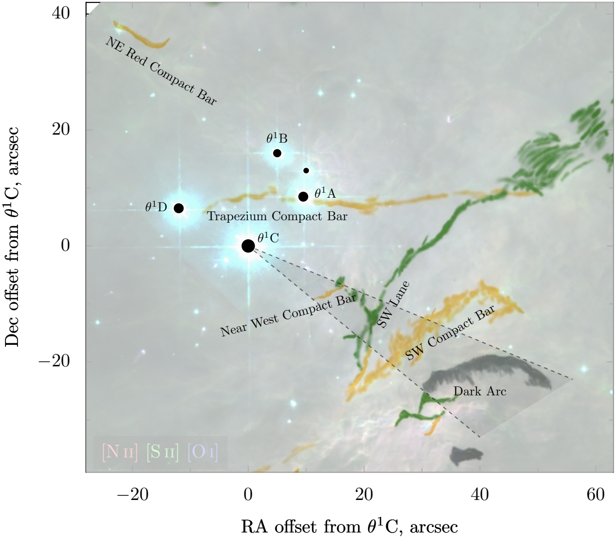
Bright bars and dark lanes



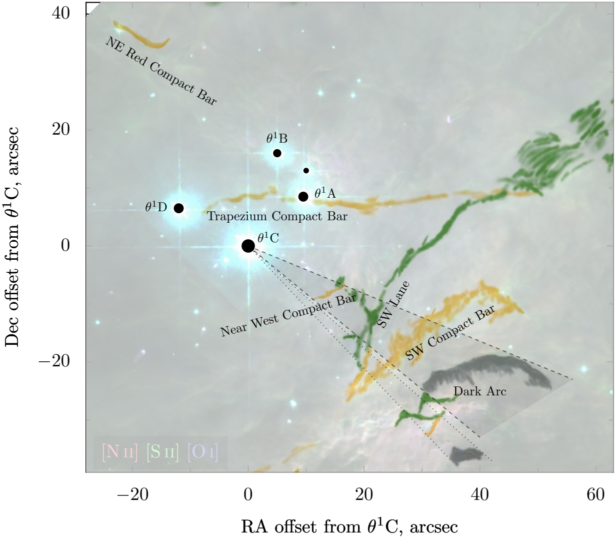
Bright bars and dark lanes



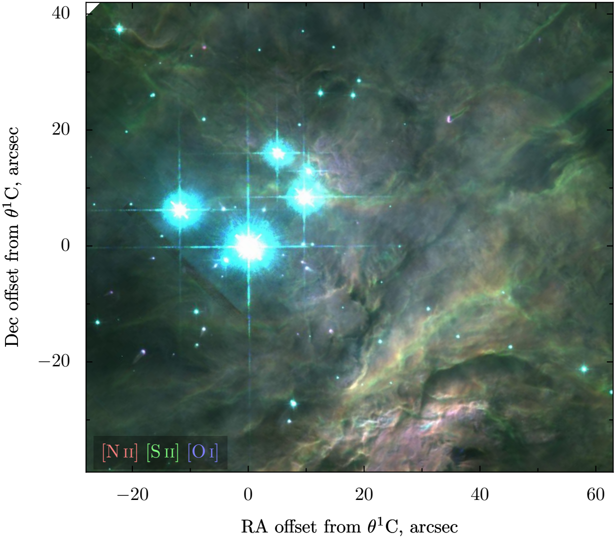
Bright bars and dark lanes



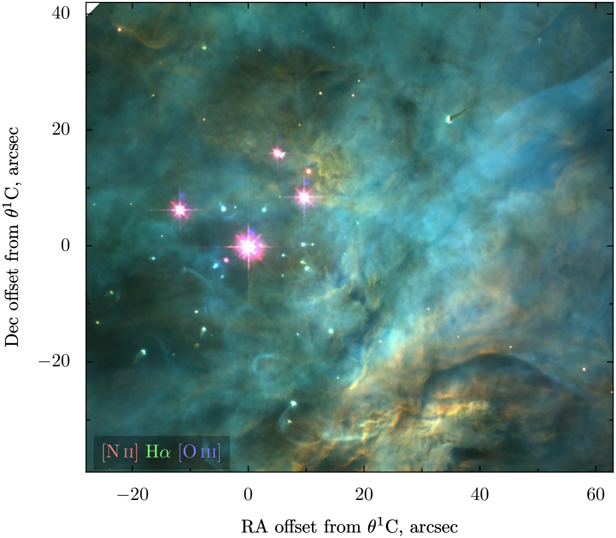
Bright bars and dark lanes



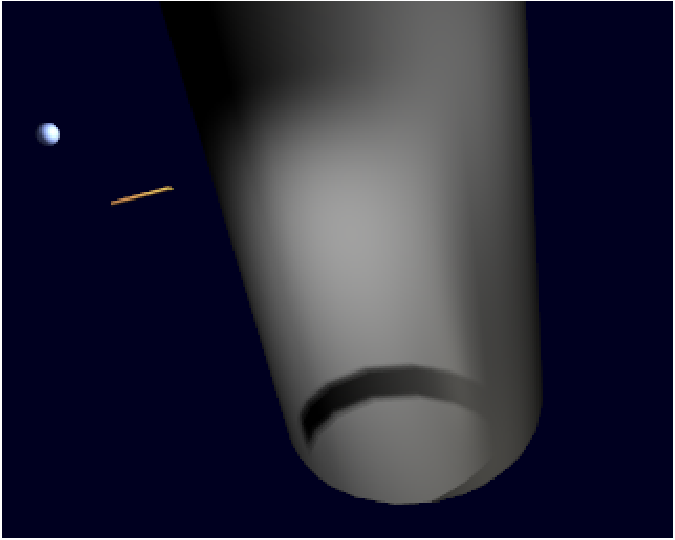
Bright bars and dark lanes



Bright bars and dark lanes

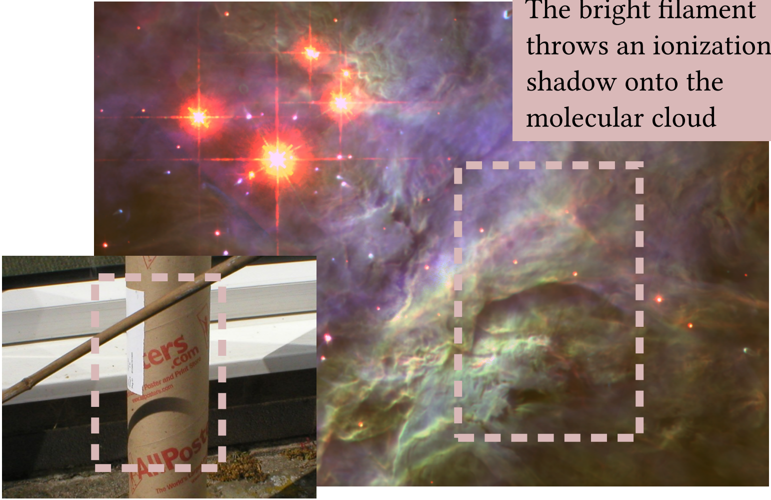


Shadow cast onto a curved screen



Shadow cast onto a curved screen

The bright filament throws an ionization shadow onto the molecular cloud



Plan of the talk

What we want to explain

Physical ingredients

- Governing equations
- Ionization balance
- Radiative transfer
- Body forces
- Magnetic fields

Building blocks for the internal dynamics

Application of H II region models to Orion

What about the stellar wind?

Governing equations

Euler equations

Conservation of mass, **momentum**, energy

Ionization balance

Global and local ionization parameter

Radiative transfer

Ionizing radiation, non-ionizing radiation, X-rays

Want more details?

See Henney `2007dmsf.book..103H`

Euler equations

Mass: $$\frac{\partial\rho}{\partial t} + \underline{\nabla}\cdot(\rho\underline{u}) = 0$$

ρ : density $\underline{u}$: velocity

Momentum: $$\frac{\partial}{\partial t}(\rho\underline{u}) + \underline{\nabla}(P + \rho u^2) = \underline{a}\rho$$

Non-steady evolution

Steady state gradients

Body forces

P: Pressure (gas + magnetic)

$\underline{a}$: acceleration (gravity, radiation ...)

Ionization balance

Local ionization parameter

Dimensionless ratio of ionizing photon density to gas particle density

$$\Upsilon = \frac{F_{\mathrm{ion}}}{cn}$$

In static equilibrium, the Hydrogen ionization fraction x satisifies

$$\frac{x^2}{1 - x} \simeq 3 \times 10^5\, \Upsilon$$

Ionization balance

Global ionization parameter

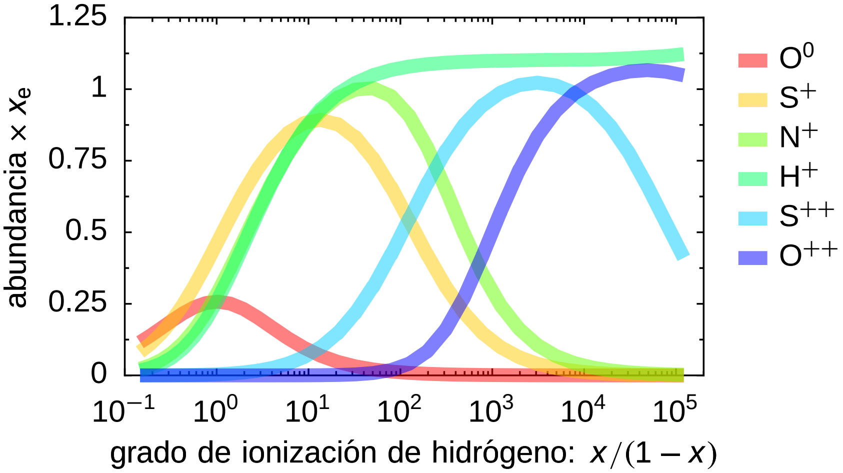
For static, ionization-bounded region:

$$\langle \Upsilon \rangle \simeq 0.006 \left(\frac{\langle n \rangle_{\mathrm{rms}}}{10^3\ \mathrm{cm}^{-3}} \right)^{1/3} \left(\frac{Q_{\mathrm{H}}}{10^{49}\ \mathrm{s}^{-1}} \right)^{1/3}$$

- For a given dust-gas ratio, dust opacity is more important at high $\langle \Upsilon \rangle$
- Advective (flow) terms are globally more important in the ionization and heating/cooling balance for low $\langle \Upsilon \rangle$

Ionization balance

Heavy-element ionization



Radiative transfer

Ionizing radiation

- All absorbed in H II region (or ionization front)
- Higher density gas absorbs more efficiently (per unit mass)

FUV/optical radiation

Some absorbed in H II region but mainly in near PDR (PAH excitation)

X rays

- Produced by T Tauri chromospheres: $\sim 1\ L_\odot$
- Produced by base of O star wind: $\sim 1\ L_\odot$
- Produced by shocked stellar wind bubble: $\sim 0.01\ L_\odot$
- Absorbed in far PDR and molecular gas

Body forces

Gravity

Only important in the molecular gas

Radiation pressure

- Trapped resonance lines (e.g., Lyman α)
- Ionizing radiation momentum acting directly on gas
  - Only important for *very* high ionization parameter, Υ
- **Lower energy radiation absorbed by dust**
  - Important for high ionization parameter, Υ
  - Collisionally coupled to gas

Magnetic fields

No time today! **But please see . . .**

Mon. Not. R. Astron. Soc. **398,** 157–175 (2009) doi:10.1111/j.1365-2966.2009.15153.x

Radiation-magnetohydrodynamic simulations of the photoionization of magnetized globules★

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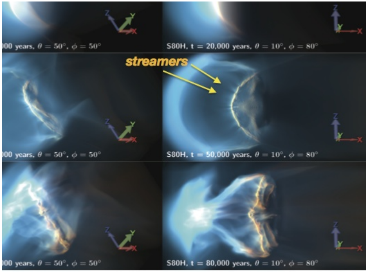

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Radiation-magnetohydrodynamic simulations of H II regions and their associated PDRs in turbulent molecular clouds

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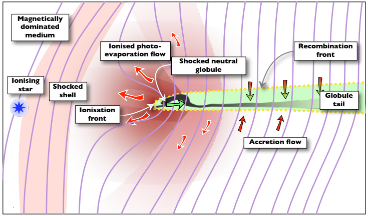


Plan of the talk

What we want to explain

Physical ingredients

Building blocks for the internal dynamics

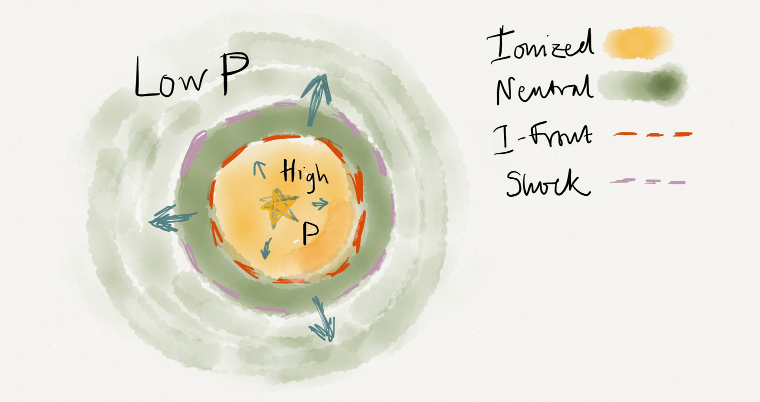
- Thermal pressure gradients
- Steady-state photoevaporation flows
- Winds, shocks, shells

Application of H II region models to Orion

What about the stellar wind?

Thermal pressure gradients . . .

. . . drive the non-steady global expansion of the H II region

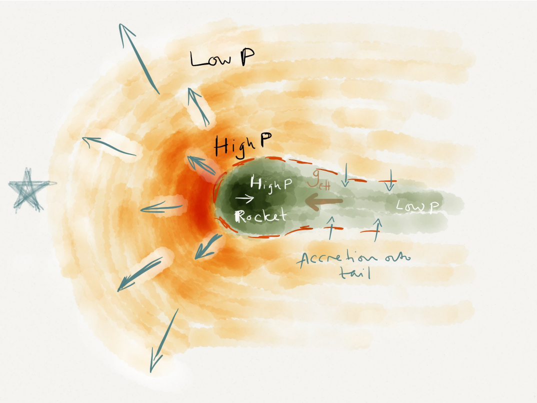


Note that the neutral gas expands faster than the ionized gas.

Thermal pressure gradients . . .

. . . drive steady-state photoevaporation flows

From globules, filaments, escarpments, proplyds, etc



Here, the ionized gas moves fastest.

Steady flow down a pressure gradient

Steady-state continuity equation

$$\rho u r^k = \text{constant} \quad k = \begin{cases} 0 & \text{(plane)} \\ 1 & \text{(cylindrical)} \\ 2 & \text{(spherical)} \end{cases}$$

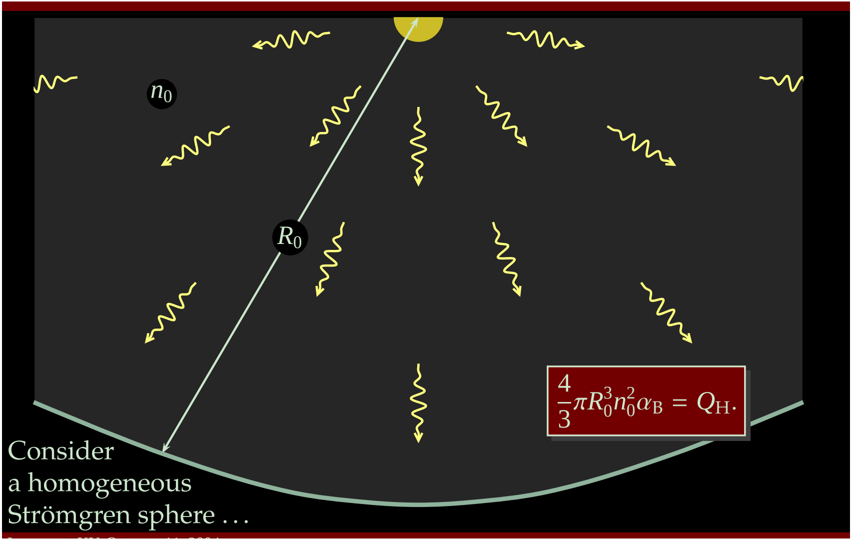
Isothermal Bernoulli equation

$$\frac{1}{2} u^2 + c_0^2 \ln \rho + \Phi = \text{constant along a streamline}$$

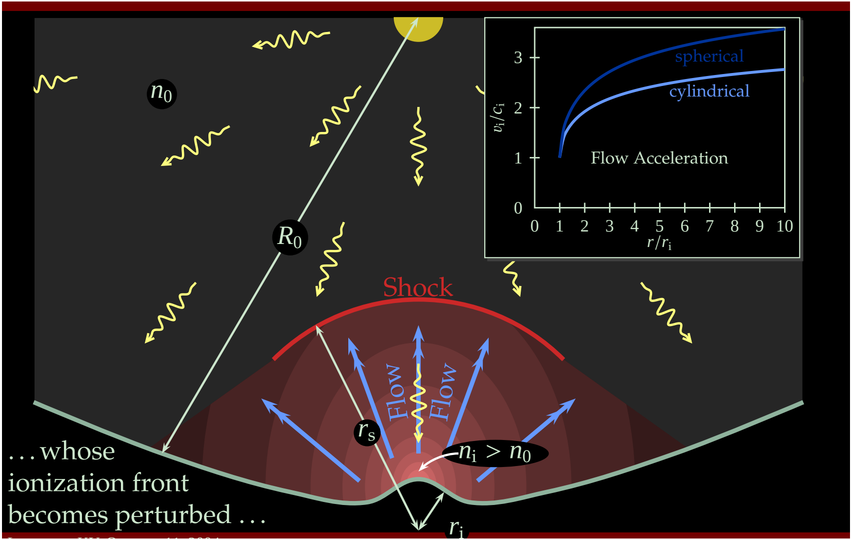
Condition for acceleration of a diverging flow

$$\frac{du}{dr} > 0 \quad \text{if} \quad u > c_0 \quad \text{and} \quad k > 0$$

Corrugated ionization fronts

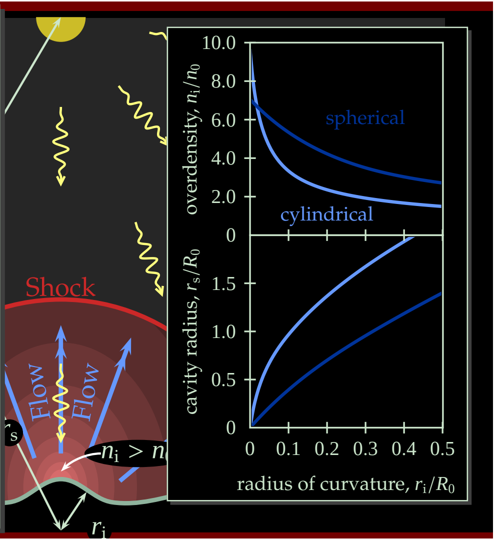


Corrugated ionization fronts



Corrugated ionization fronts

- The flows from relatively small undulations can evacuate cavities with size comparable to that of the entire H II region.
- Flow brightness ∝ cavity radius.
- Flows from shorter-wavelength undulations have higher peak densities (up to $10n_0$) but are fainter.

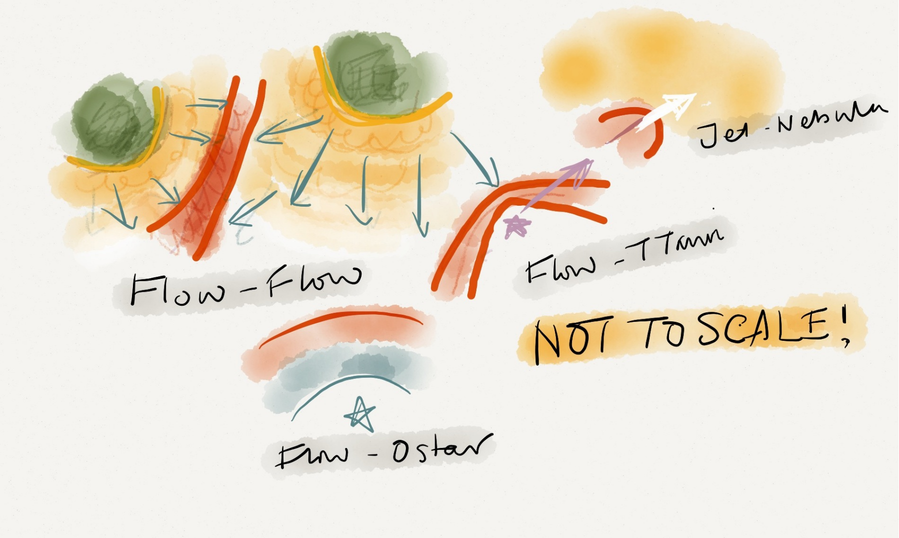


Photoevaporation of isolated globules   Henney et al. (2009)

[N II]   Hα   [O III]

Winds, shocks, shells

No time today!



Plan of the talk

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Application of H II region models to Orion
- Simple models
- Turbulent models

What about the stellar wind?

Application of H II region models to Orion

Simple models

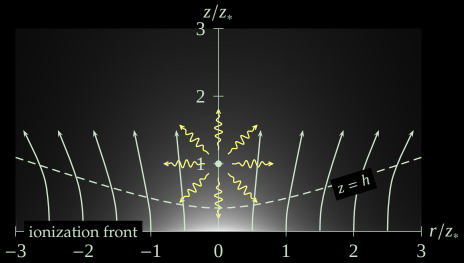
- **Analytic calculation** or numerical simulations
- High degree of symmetry (1D plane or **2D cylindical**)
- Possibility to include realistic microphysics

Turbulent models

- Numerical simulations only
- Fully 3D, no particular symmetry imposed
- **But** …
  - Simplified microphysics, albeit a big improvement on the competition!
  - Uncertain initial conditions

Steady flow from a plane ionization front

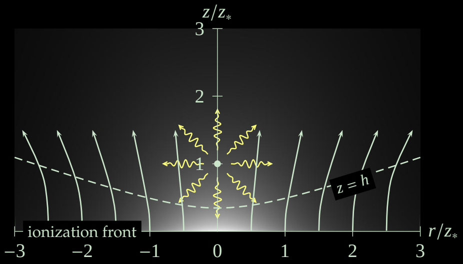
- Zeroth order approximation to dynamics of Orion nebula.
- Divergence of radiation field drives (weaker) divergence of evaporation flow.



- An approximate steady-state solution can be found by combining ionization balance with the isothermal Bernoulli equation, assuming "prompt" bending of the streamlines.

Steady flow from a plane ionization front

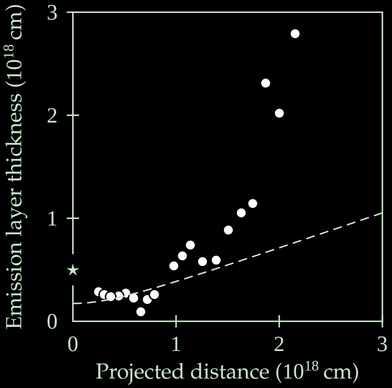
- Scale height on the axis is $h_0 = 0.346 z_*$.
- At large radii, the streamline angle tends towards an asymptotic value: $i_\infty = \tan^{-1} 0.346 \simeq 19°$.



- Scale height increases with radius as $h \sim (1 + (r/z_*)^2)^{1/2}$.
- Density at ionization front drops with radius as $n \sim (1 + (r/z_*)^2)^{-2}$.

Steady flow from a plane ionization front

- Baldwin et al. (1991) derived the thickness of the emitting layer in Orion Nebula:
  - Surface brightness of the Paschen 11–3 line $\Rightarrow \int n^2\, dz \Rightarrow n^2 h$
  - Intensity ratio of the [S II] doublet $\Rightarrow n$.

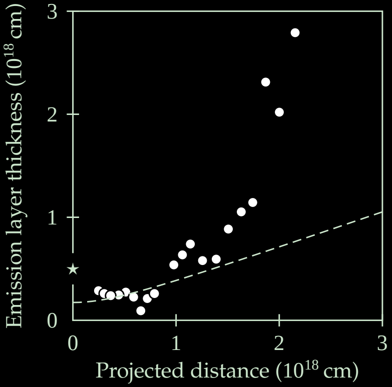


- In the inner region, this result agrees very well with the model prediction (**without any free parameters!**)

Steady flow from a plane ionization front

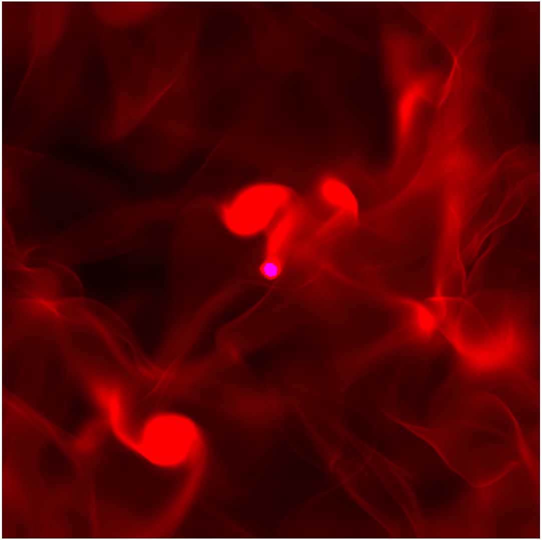
However, there remain some problems:

- Observationally, $n \sim r^{-1.63}$, while the model predicts $n \sim r^{-2}$.
- $\Rightarrow$ could be due slight concavity in the i-front on large scales.



- It is also obvious that the front has many irregularities with scales between $\simeq 10^{16}$ and 3×10^{17} cm.

Turbulent models: initial conditions



Turbulent models: state of play

Physics we have

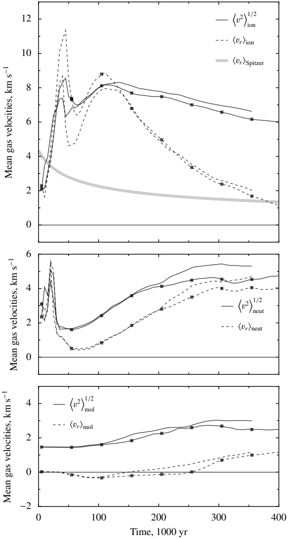
- 3D time-dependent, hydrodynamics
- Approximate radiative transfer
- Microphysics:
  - good for ionized gas
  - fair for PDR
  - poor for molecular gas
- [Ideal magnetohydrodynamics]

Physics we lack

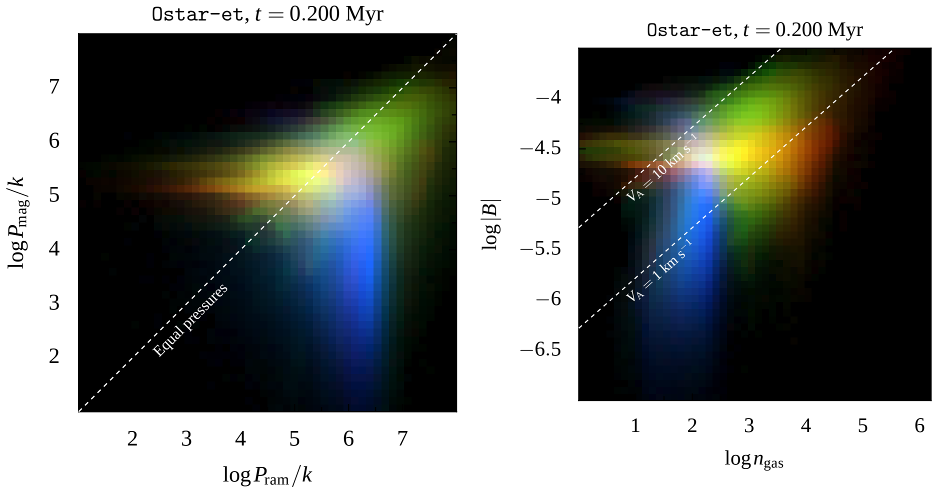
- Stellar winds
- Radiation pressure
- Diffuse field
- Self-gravity
- Better microphysics, better radiative transfer, multifluids, non-ideal MHD, κ-distributions, etc …

Turbulent models: results

- Many morphological features of observed H II regions are reproduced naturally
  - Due to existing density structure in the turbulent molecular cloud, combined with fragmentation induced by interaction with the ionized gas
- Velocity dispersions of order the sound speed are maintained in the ionized gas during the entire evolution
- The highest pressure neutral/molecular gas is driven to equipartition between thermal, magnetic, and turbulent energies
- Lower pressure gas bifurcates into zones dominated by one or the other



Turbulent models: more results



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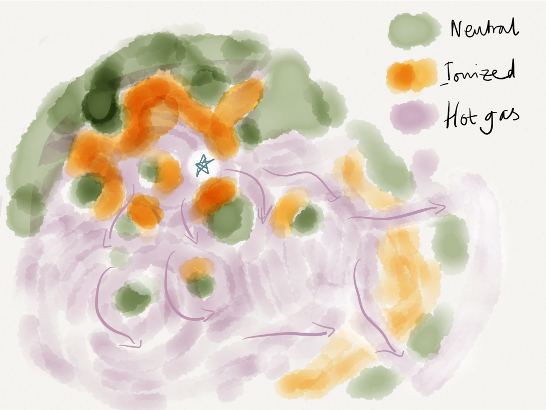
Why is the X-ray gas seen only in the EON?

Momentum-driven versus energy-driven

Percolation of the shocked wind

- Hot gas pressure should be roughly uniform (high sound speed, low Mach number)
- Ionized gas pressure is 100 times higher in inner Huygens region than in outer EON (causally disconnected).
- Therefore, volume filling factor of hot gas in inner region should be very small



"Predicted" X-ray emission

Momentum-driven wind

Energy-driven wind

Conclusions

- We understand some things …
- … we are working on figuring out the rest.
- *Thanks for sharing all the data, Bob!*