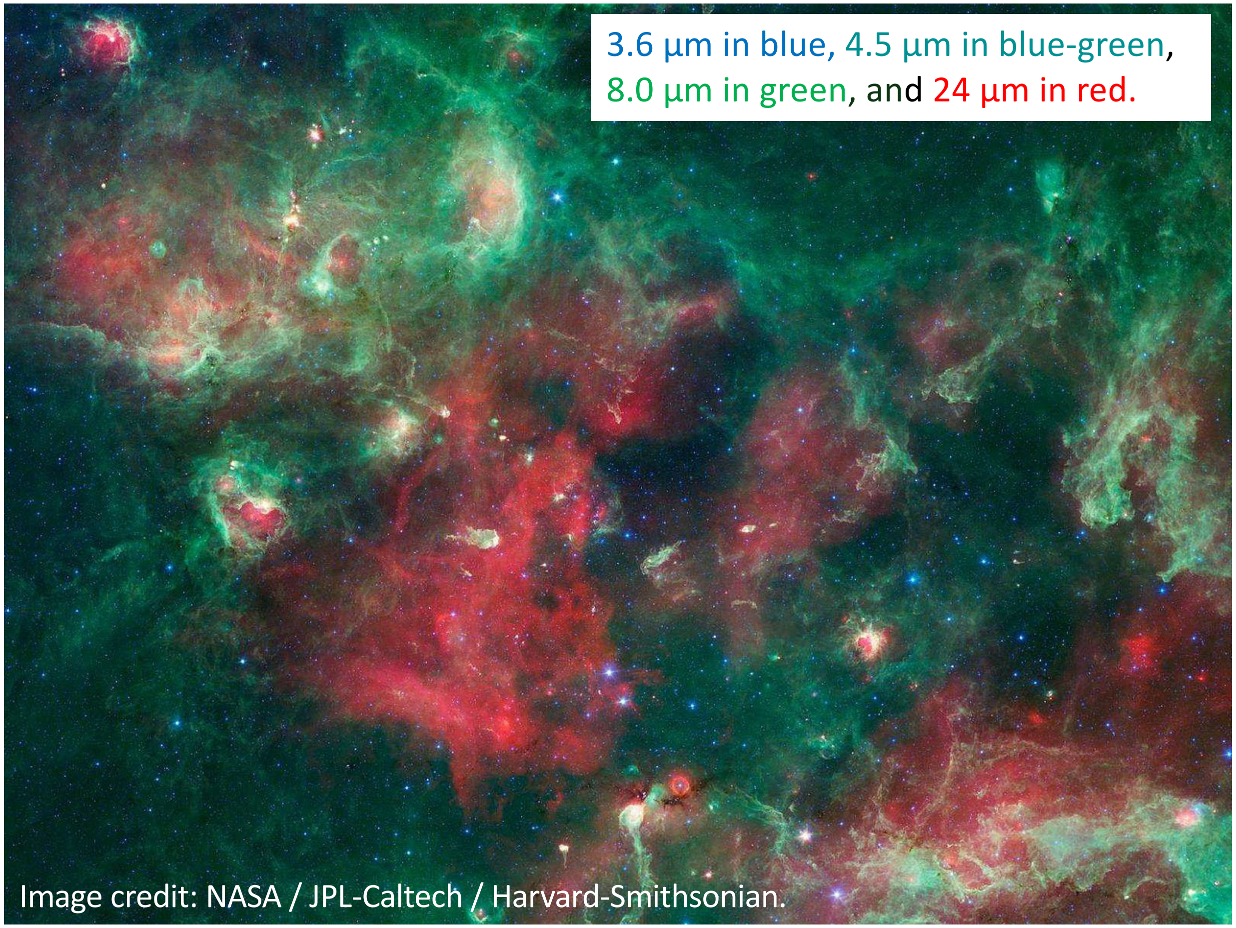
Ionized Gas

HII Regions
Recombination Lines
Free-Free Emission



Cygnus X Star Forming region as imaged by the Spitzer Space Telescope →

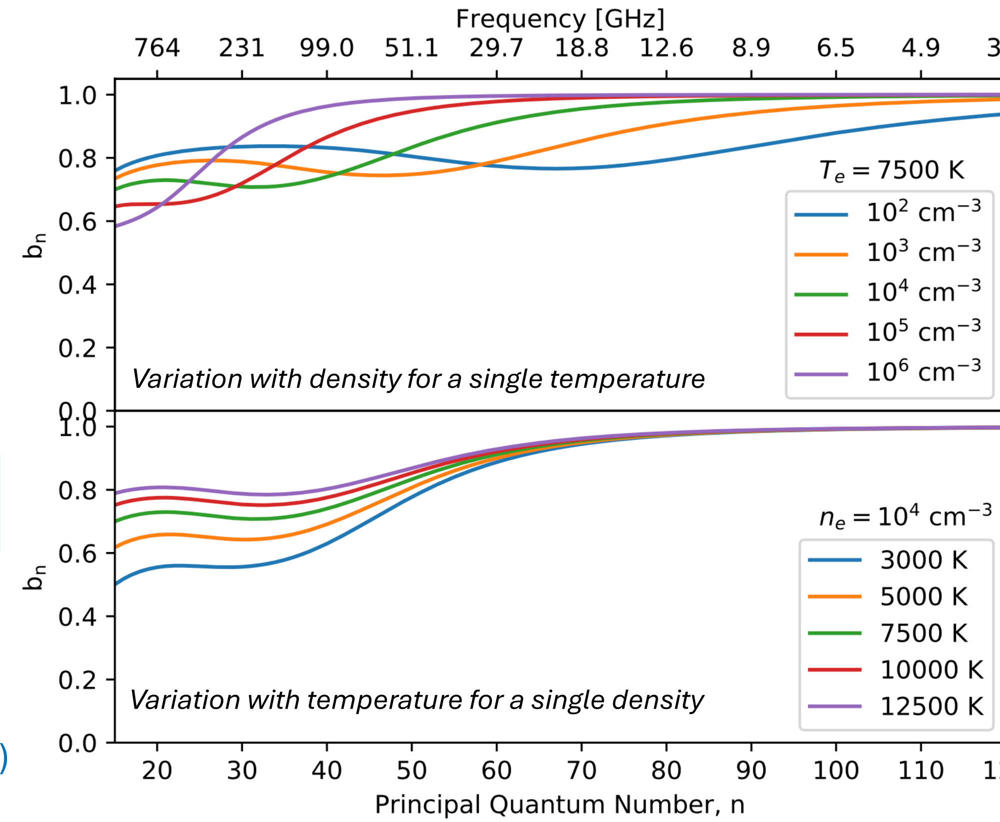
Radio Recombination Lines (ERA 7.2, 7.6)

Radiative Transfer! (7.6.1)

LTE does not apply to all recombination lines

The departure (from LTE) coefficient of spontaneous emission, b_n, shown as a function of principal quantum number (frequency) →

Deviation from LTE at low density, low temperature and low quantum number



Emig Thesis (2021)

Radio Recombination Lines (ERA 7.2, 7.6)

Radiative Transfer! (7.6.1)

If we are in LTE limit:

Remember, the line opacity coefficient in LTE is:

$$\kappa(\nu) = \frac{c^2}{8\pi\nu_0^2}\frac{g_U}{g_L}n_L A_{UL}\left[1 - \exp\left(-\frac{h\nu_0}{kT}\right)\right]\phi(\nu) \quad (7.67)$$

The book finds for the n → n + 1 electronic transition of hydrogen (see book for derivation w/ Saha Equation)

$$\kappa(\nu_0) \approx \left(\frac{n_e^2}{T_e^{5/2}\Delta\nu}\right)\left(\frac{4\pi e^6 h}{3m_e^{3/2}k^{5/2}c}\right)\left(\frac{\ln 2}{2}\right)^{1/2}. \quad (7.94)$$

Valid for all radio recombination lines with n >> 1. Dependence on 'n' gone!

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The **optical depth** becomes defined by an **Emission Measure:**

$$\frac{\text{EM}}{\text{pc}\ \ \text{cm}^{-6}} \equiv \int_{\text{los}}\left(\frac{n_e}{\text{cm}^{-3}}\right)^2 d\left(\frac{s}{\text{pc}}\right). \quad (7.95)$$

Where the line opacity is,

$$\tau_L \approx 1.92\times10^3\left(\frac{T_e}{\text{K}}\right)^{-5/2}\left(\frac{\text{EM}}{\text{pc}\ \ \text{cm}^{-6}}\right)\left(\frac{\Delta\nu}{\text{kHz}}\right)^{-1}. \quad (7.96)$$

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Notice what this depends on!
See where this is going…?

Radio Recombination Lines (ERA 7.2, 7.6)

Radiative Transfer! (7.6.1)

Because the line opacity in HII region is **optically thin τ**<<1, the **brightness temperature** contributed by a recombination emission line at its center frequency is,

$$T_L \approx T_e \tau_L \approx 1.92 \times 10^3 \left(\frac{T_e}{K}\right)^{-3/2} \left(\frac{EM}{pc\ \ cm^{-6}}\right) \left(\frac{\Delta\nu}{kHz}\right)^{-1}. \quad (7.97)$$

A direct probe of electron temperature, T_e, and EM!

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A direct probe of electron temperature, T_e, and EM!

And at frequencies high enough that that the line continuum (free-free; we will get to this next!), T_C is also optically thin the peak line-to-continuum ratio in LTE can be used to explicitly find T_e

$$\left(\frac{T_e}{K}\right) \approx \left[7.0 \times 10^3 \left(\frac{\nu}{GHz}\right)^{1.1} 1.08^{-1} \left(\frac{\Delta\nu}{km\ \ s^{-1}}\right)^{-1} \left(\frac{T_C}{T_L}\right)\right]^{0.87}. \quad (7.99)$$

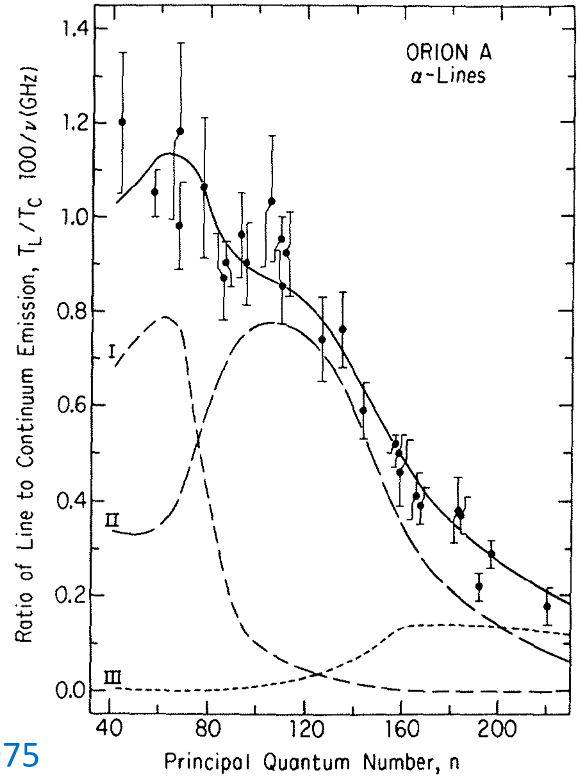
Main Takeaway:

The **line-to-continuum ratio yields an estimate of the electron temperature T_e** that is independent of the emission measure (opacity) so long as the frequency is high enough that the continuum optical depth is small.

Radio Recombination Lines (ERA 7.2, 7.6)

Radiative Transfer! (7.6.1)

Mapping the temperature distribution in the HII Region of the Orion Nebula:



Lockman and Brown 1975

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The **line-to-continuum ratio yields an estimate of the electron temperature T_e** that is independent of the emission measure (opacity) so long as the frequency is high enough that the continuum optical depth is small.

Fig. 7.8 (ERA)

Table 2.3. Lockman-Brown model of the Orion Nebula.[a]

Region	Temperature (K)	N_e(cm^{-3})	Angular size (arcmin)	Linear size (pc)
I	(7,500)	$10^{4.5}$	0.33	0.043
II	(10,000)	$10^{3.5}$	4.3	0.56
III	(12,500)	($10^{2.3}$)	19.1	2.5

[a] Quantities in parentheses are determined by the recombination-line observations.

Radio Recombination Lines (ERA 7.2, 7.6)

Differences between the rest and observed frequencies of radio recombination lines are attributed to Doppler shifts from nonzero radial velocities

With a simple rotational model for the disk of our Galaxy, astronomers can convert radial → velocities to distances

They roughly outline the major spiral arms.

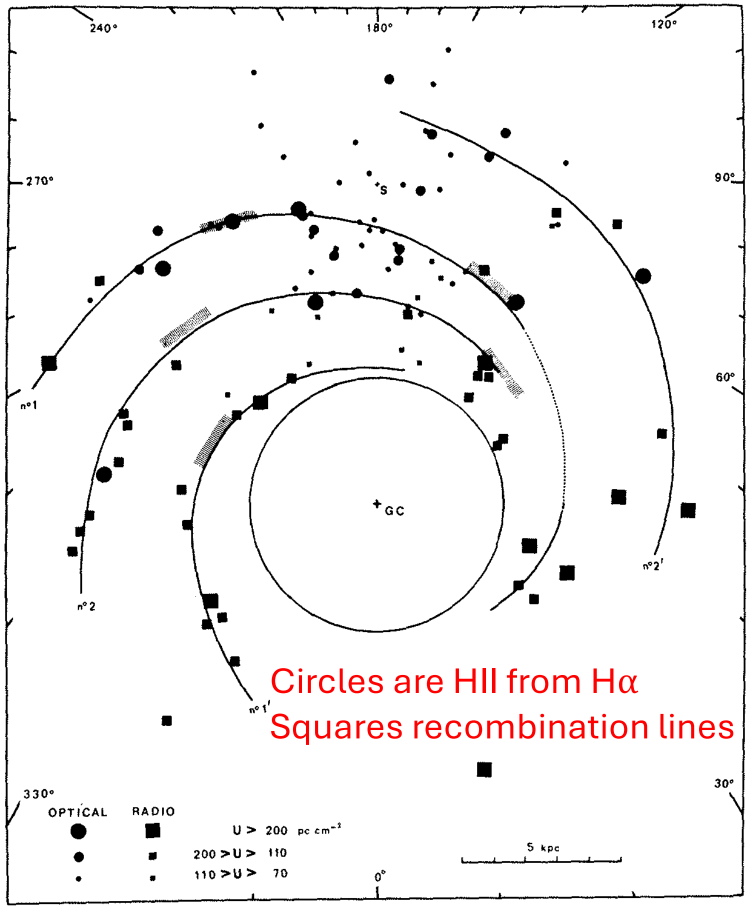


Fig. 7.9 (ERA)

Georgelin & Georgelin 1976

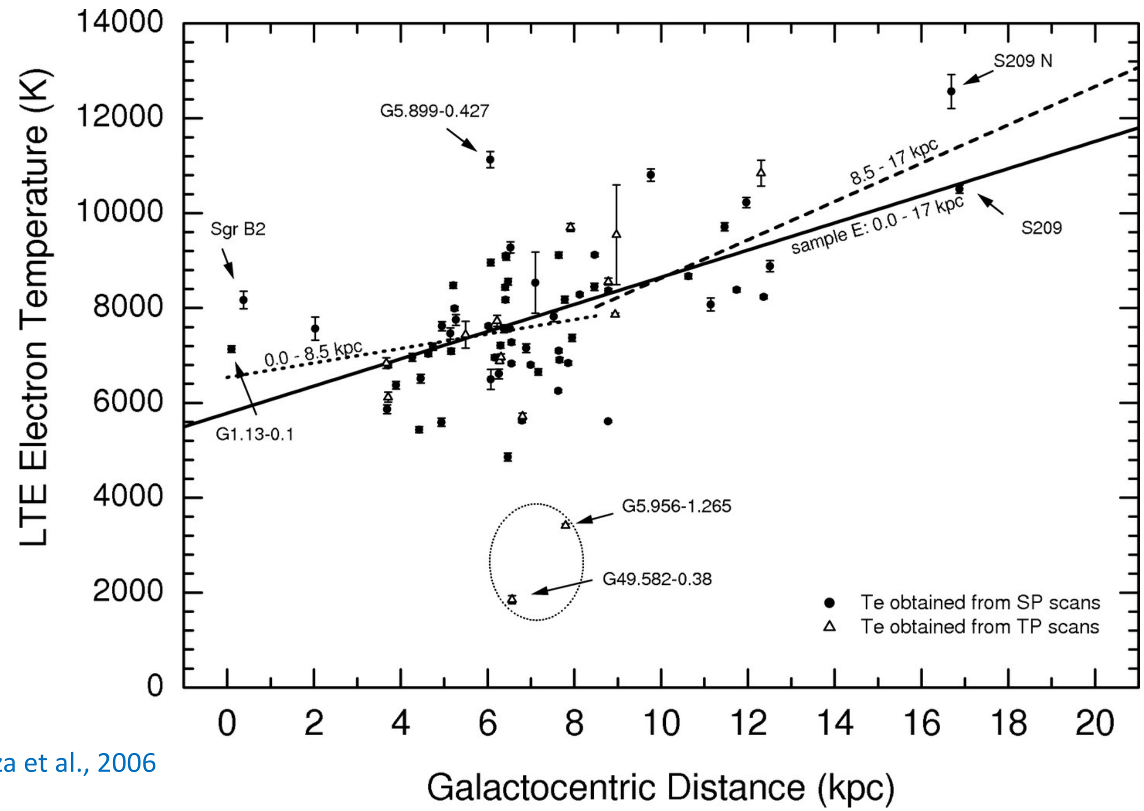
Radio Recombination Lines (ERA 7.2, 7.6)

Fig. 7.10 (ERA)

Observed electron temperatures of Galactic HII regions: **temperature increases with distance from the Galactic center →**

The explanation for this trend is the observed **decrease in *metallicity*** (relative abundance of elements heavier than helium) with galactocentric distance

Power radiated by emission lines of "metals" is the principal cause of HII region cooling.

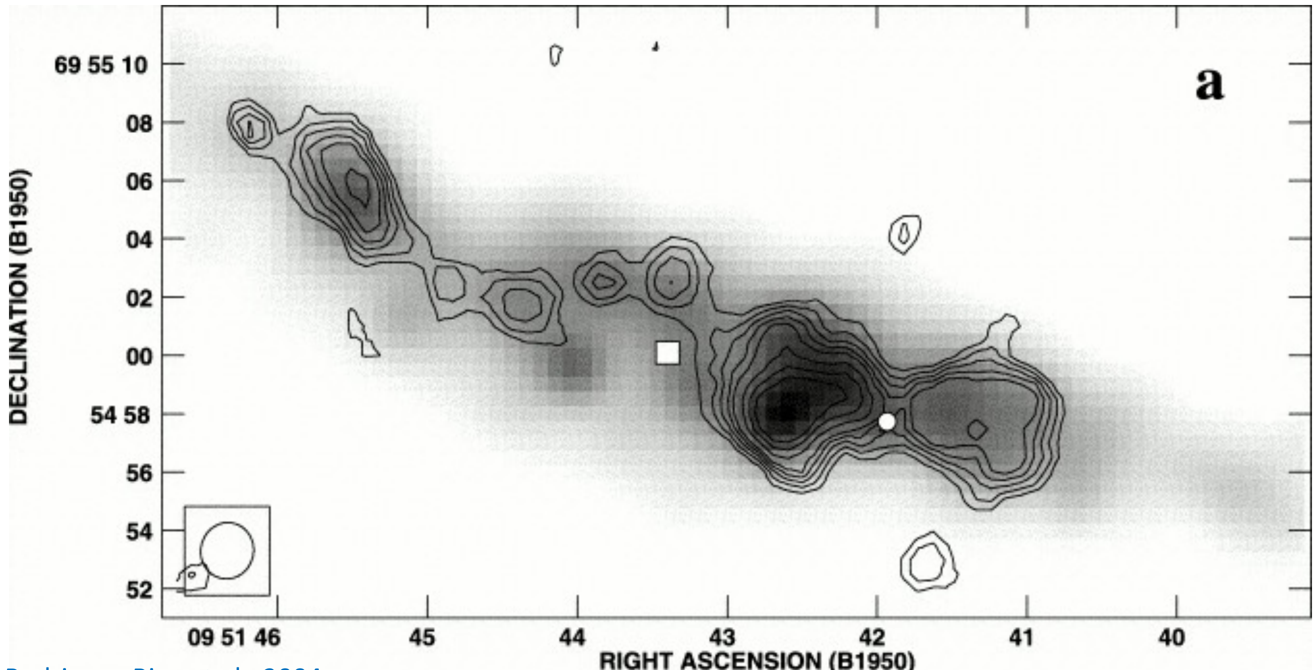


Quireza et al., 2006

Radio Recombination Lines (ERA 7.2, 7.6)

Fig. 7.11 (ERA)

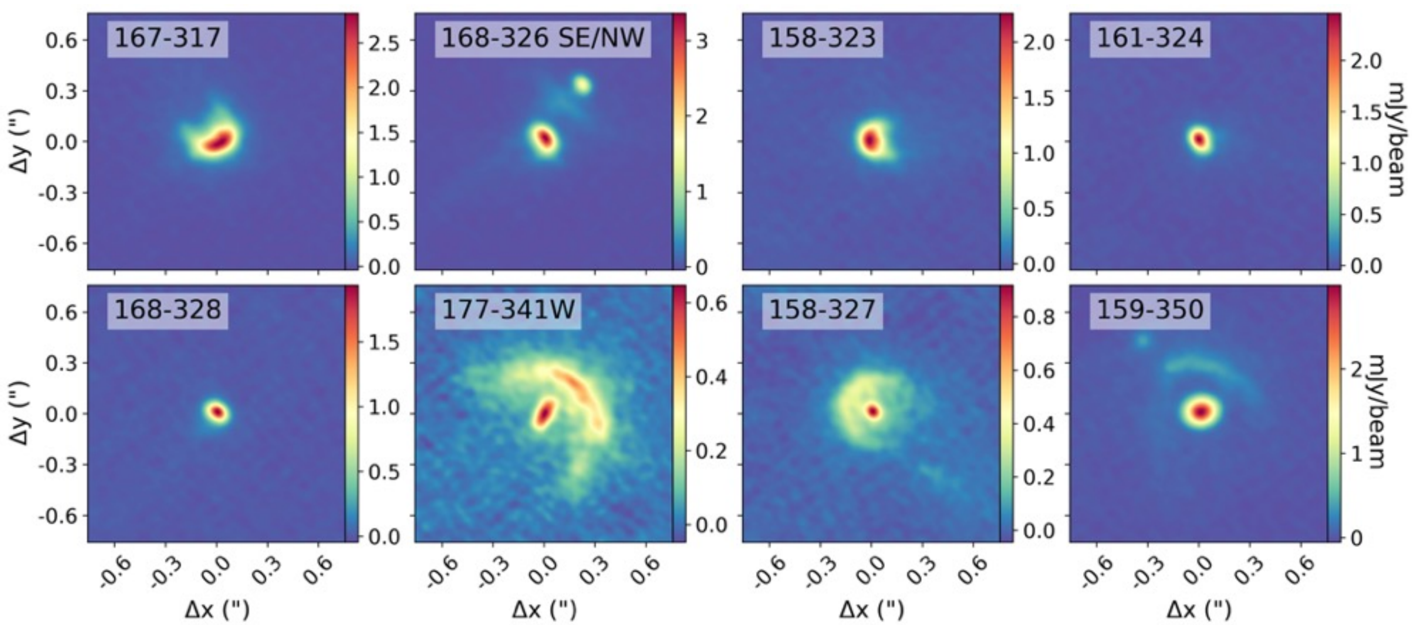
Radio recombination line strengths are much less affected by dust extinction than optical lines (e.g., the Hα and Hβ lines) are, so radio recombination lines are **useful quantitative indicators of the ionization rates** and hence star-formation rates in dusty starburst galaxies such as M82 →



Rodriguez-Rico et al., 2004

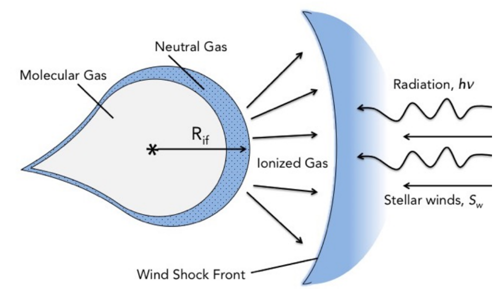
M82 imaged in H92α (contours) and 8.3 GHz free-free continuum (gray scale)

*Radio Recombination Line Emission From **Proplyds***



ALMA, Band 3 Continuum
(Ballering et al. 2023)

* Formed by ionization/ evaporation of gas in circumstellar disks around young, low-mass stars



Mini ultra-compact HII regions

Slide Credit: Ryan Boyden

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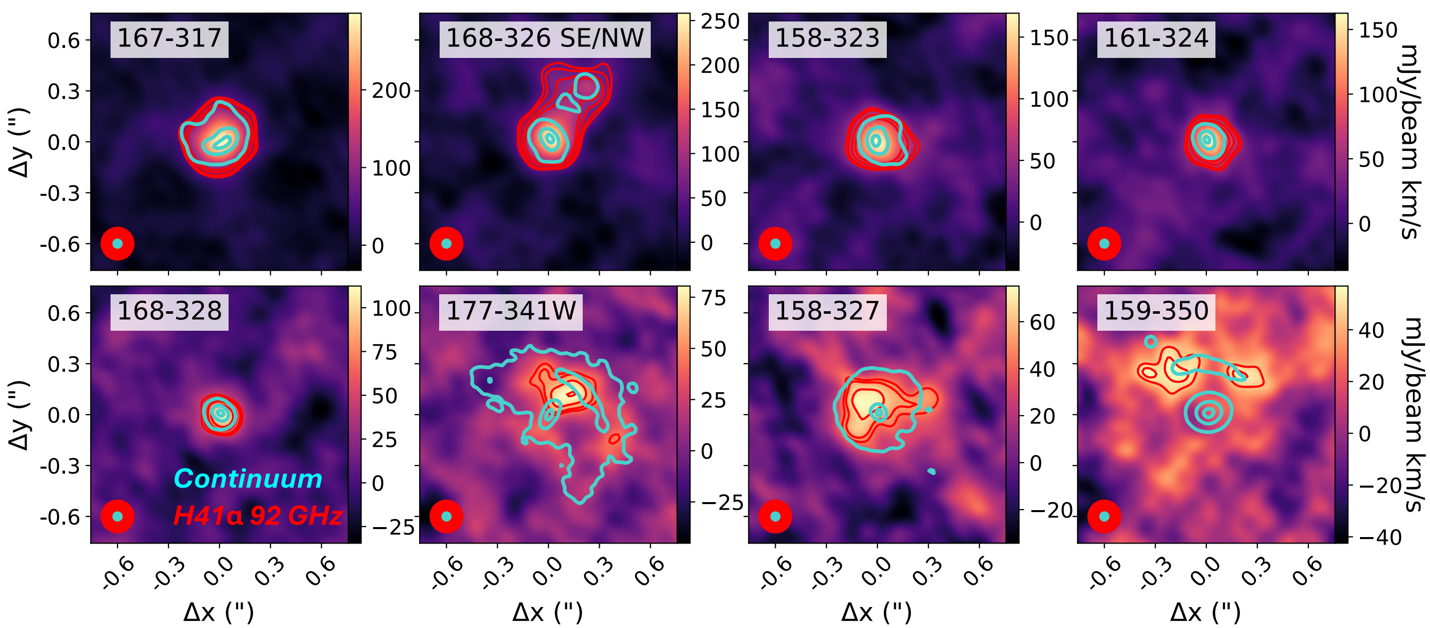

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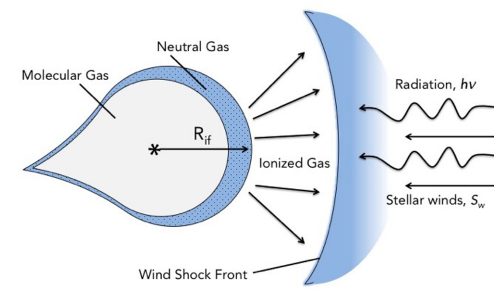
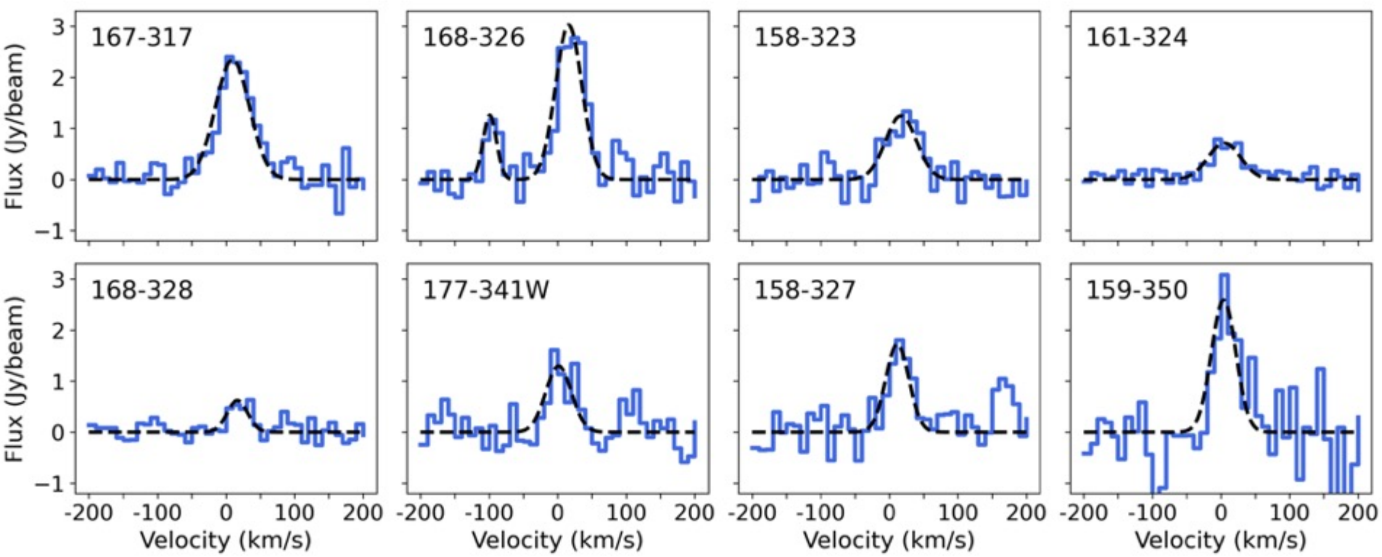


Mini ultra-compact HII regions

ALMA, H41α
(Boyden et al. in prep) -- **photoevaporating gas at the ionization front**

Slide Credit: Ryan Boyden

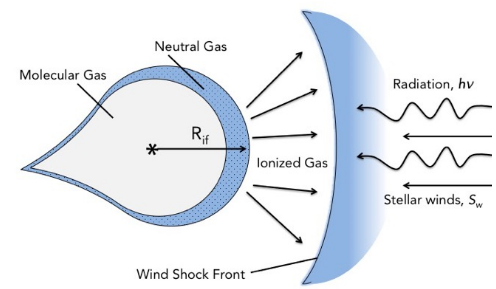
*Radio Recombination Line Emission From **Proplyds***



ALMA, H41α
(Boyden et al. in prep)

Line Widths: ~50 km/s
Dominated by ionized gas motions

* Formed by ionization/ evaporation of gas in circumstellar disks around young, low-mass stars



Mini ultra-compact HII regions

Slide Credit: Ryan Boyden

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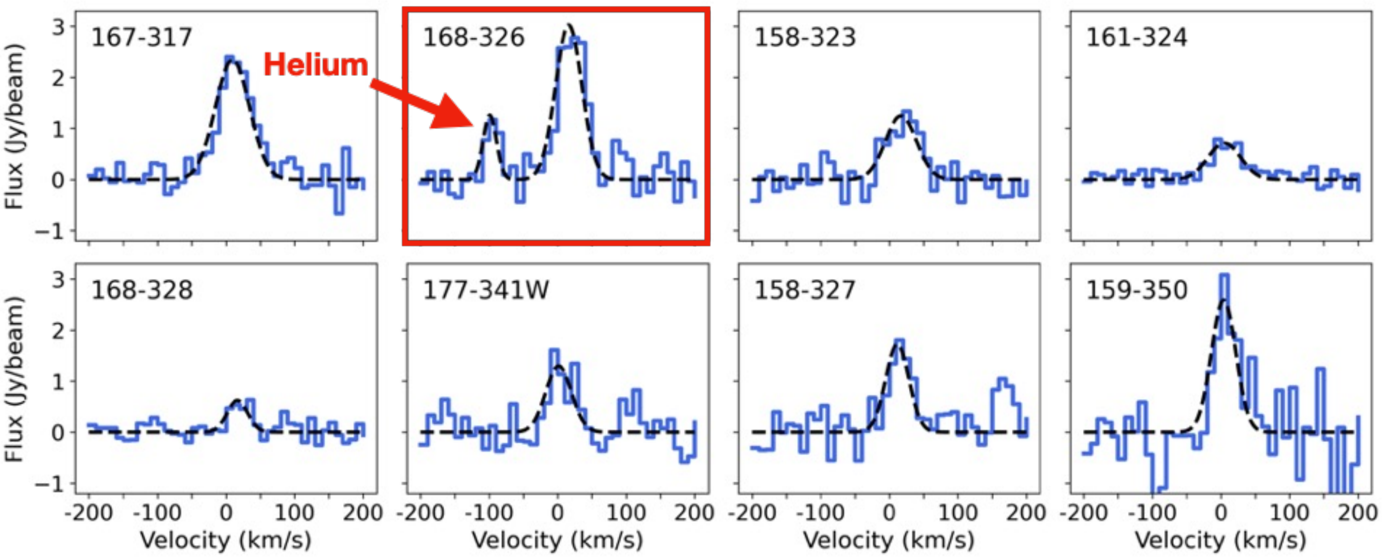

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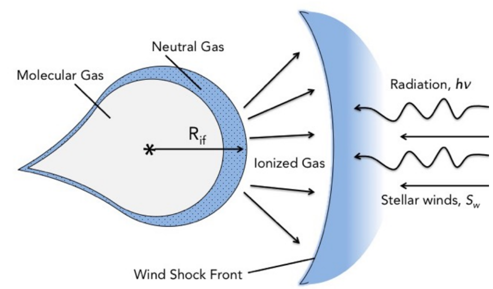


Mini ultra-compact HII regions

He/H abundance ratio: 0.2
(Helium-rich disk)

ALMA, H41α
(Boyden et al. in prep)

Slide Credit: Ryan Boyden

GREEN BANK OBSERVATORY
National Radio Astronomy Observatory

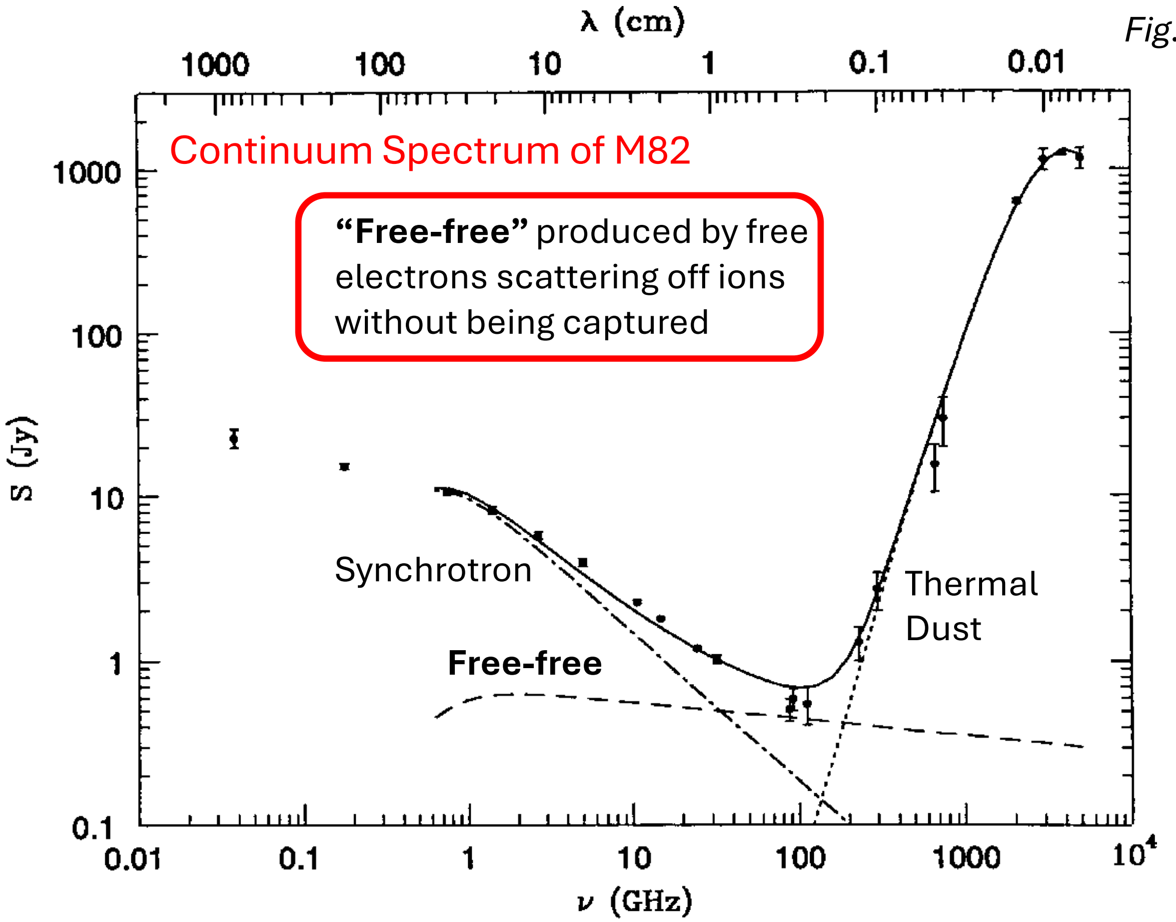
Emission Mechanisms

Spectral Lines (ERA Chap. 7)

Free-Free (ERA Chap. 4)

Synchrotron (ERA Chap. 5)

Pulsars (ERA Chap. 6)



λ (cm)
1000
100
10
1
0.1
0.01
Continuum Spectrum of M82
"Free-free" produced by free electrons scattering off ions without being captured
1000
100
10
1
0.1
S (Jy)
Synchrotron
Thermal Dust
Free-free
0.01
0.1
1
10
100
1000
10^4
ν (GHz)

Fig. 2.24 (ERA)

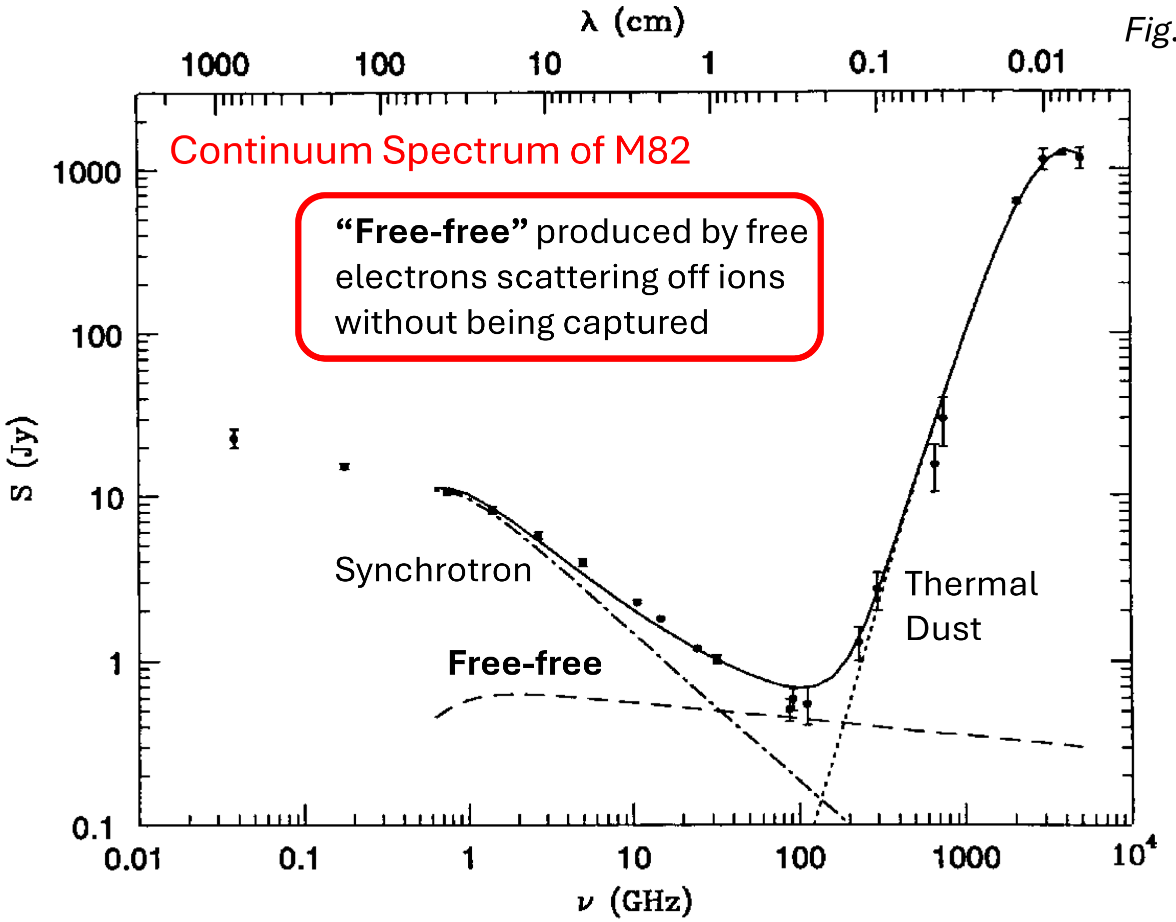
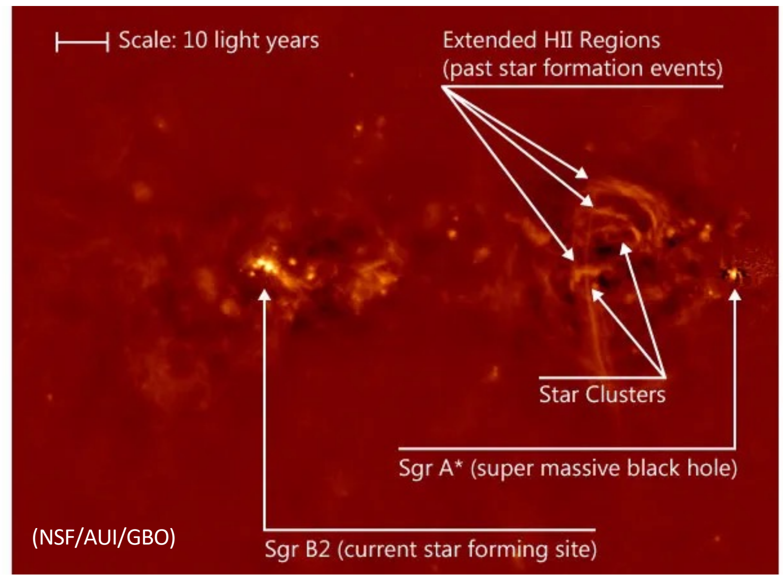


Fig. 2.24 (ERA)

Results from the **Green Bank Observatory** Continuum Instrument, MUSTANG-2, that observes the sky at wavelengths of 3mm (90 GHz)

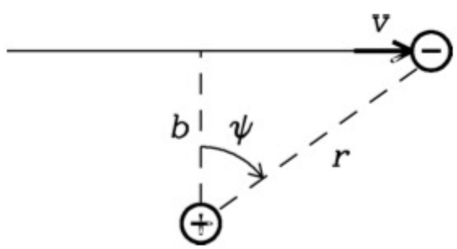


Ginsburg et al., 2020

Free-free Radiation (ERA 4.1)

Thermal and Nonthermal Emission

Free-free: the emission from a charge (e.g., electron) in the Coulomb field of another charge (ion, electron) when it experiences a small deviation in its path



The distance of closest approach, *b*, is called the impact parameter and the interval $\tau = b/v$ is the collision time.

Remember Larmor radiation power is:

$$P = \frac{2q^2\dot{v}^2}{3c^3} \qquad (4.1)$$

More generally, '**bremsstrahlung**' radiation: **electromagnetic radiation** with power P produced by accelerating (or decelerating) an electric charge *q*

NOTE: the magnetic counterpart **magnetobremsstrahlung** or "**magnetic braking radiation**" (e.g., synchrotron radiation) is covered in Chapter 5!

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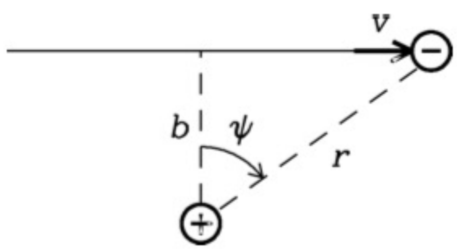

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Typically, '**thermal**' and electrons follow Maxwellian distribution

NOTE: the magnetic counterpart **magnetobremsstrahlung** or "**magnetic braking radiation**" (e.g., synchrotron radiation) is covered in Chapter 5!

Typically, '**nonthermal**' relativistic electrons w/ power-law energy distribution

Free-free Radiation (ERA 4.3)

Free-Free in HII Regions – we need to simply the problem

Main Takeaway

Only electron-ion collisions are important, and only the electrons radiate significantly

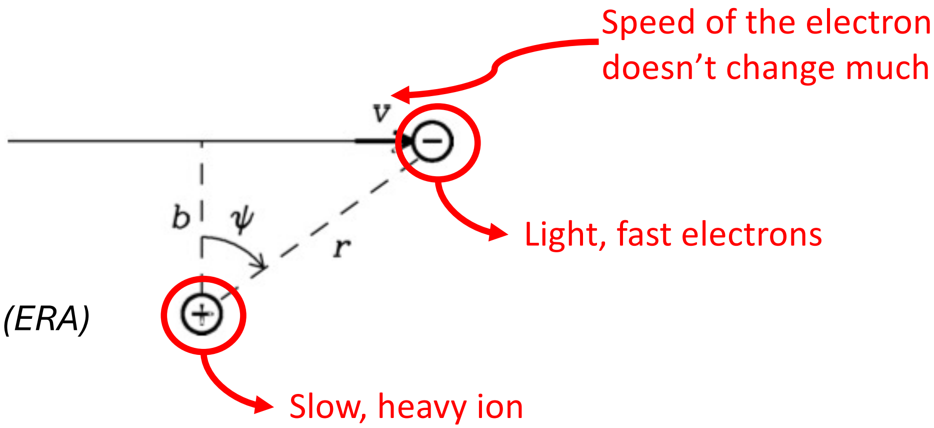

Fig. 4.2 (ERA)

The glowing Trifid Nebula HII region is revealed with near- and mid-infrared views from NASA's Spitzer Space Telescope.