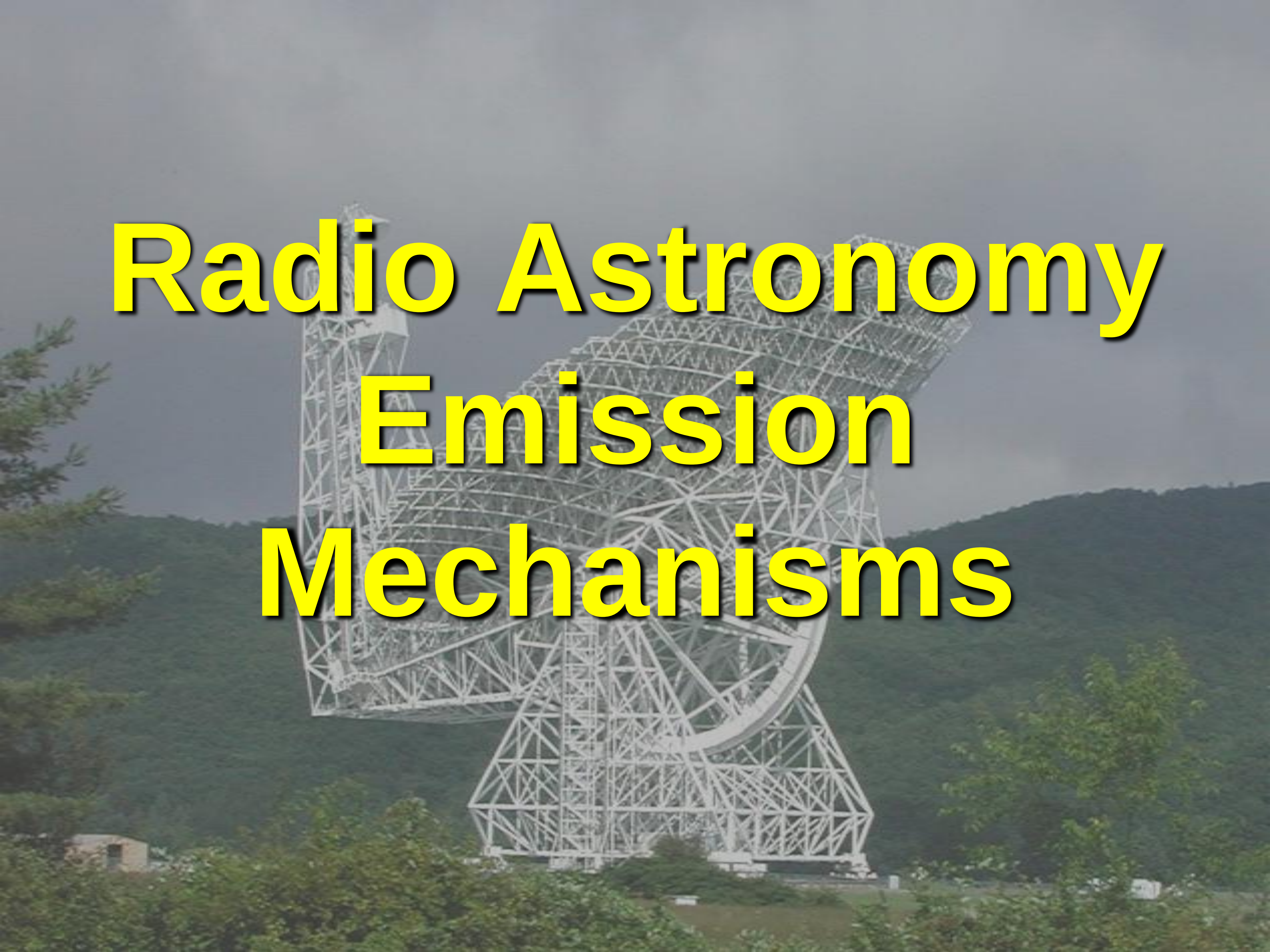
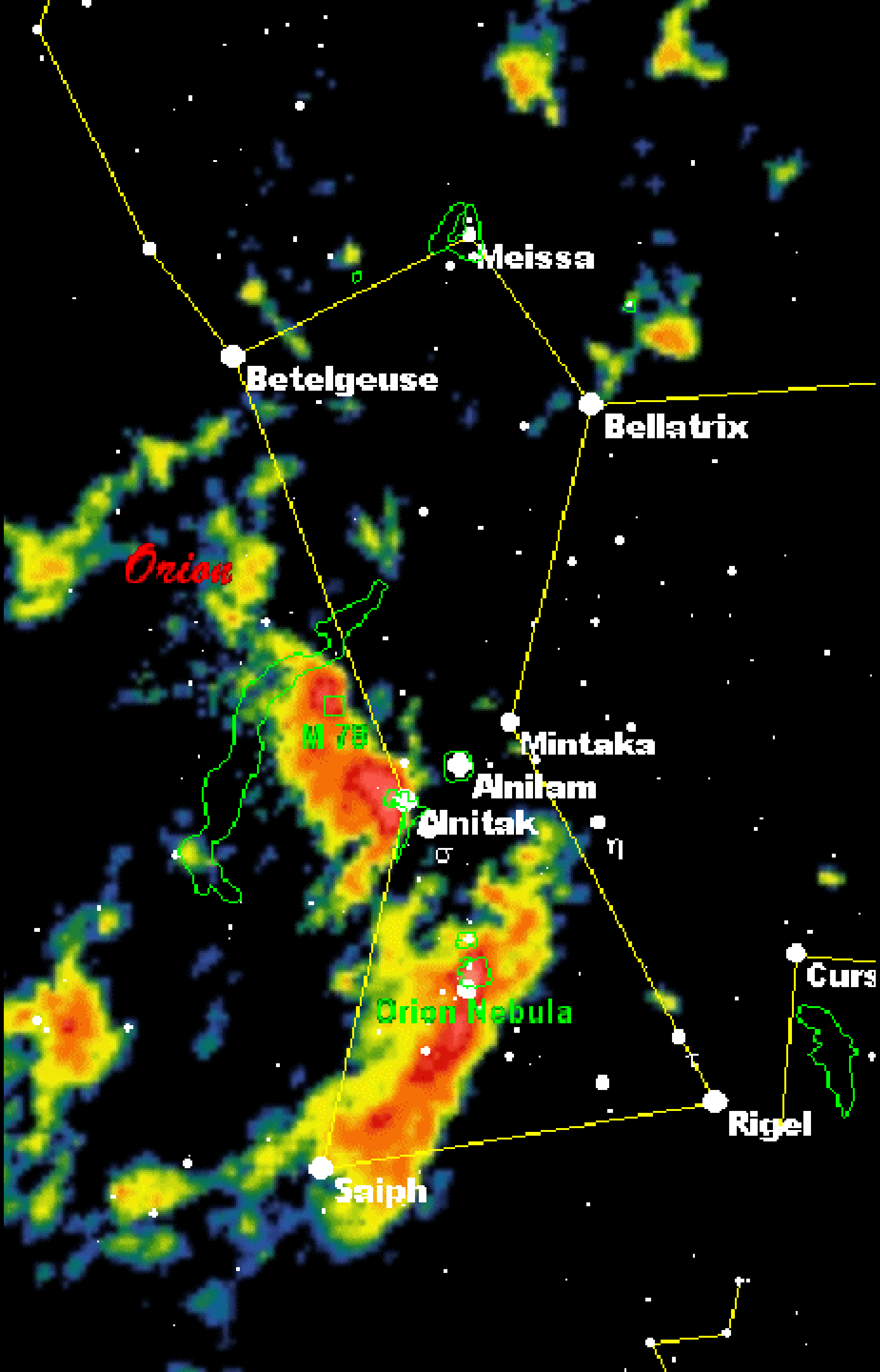
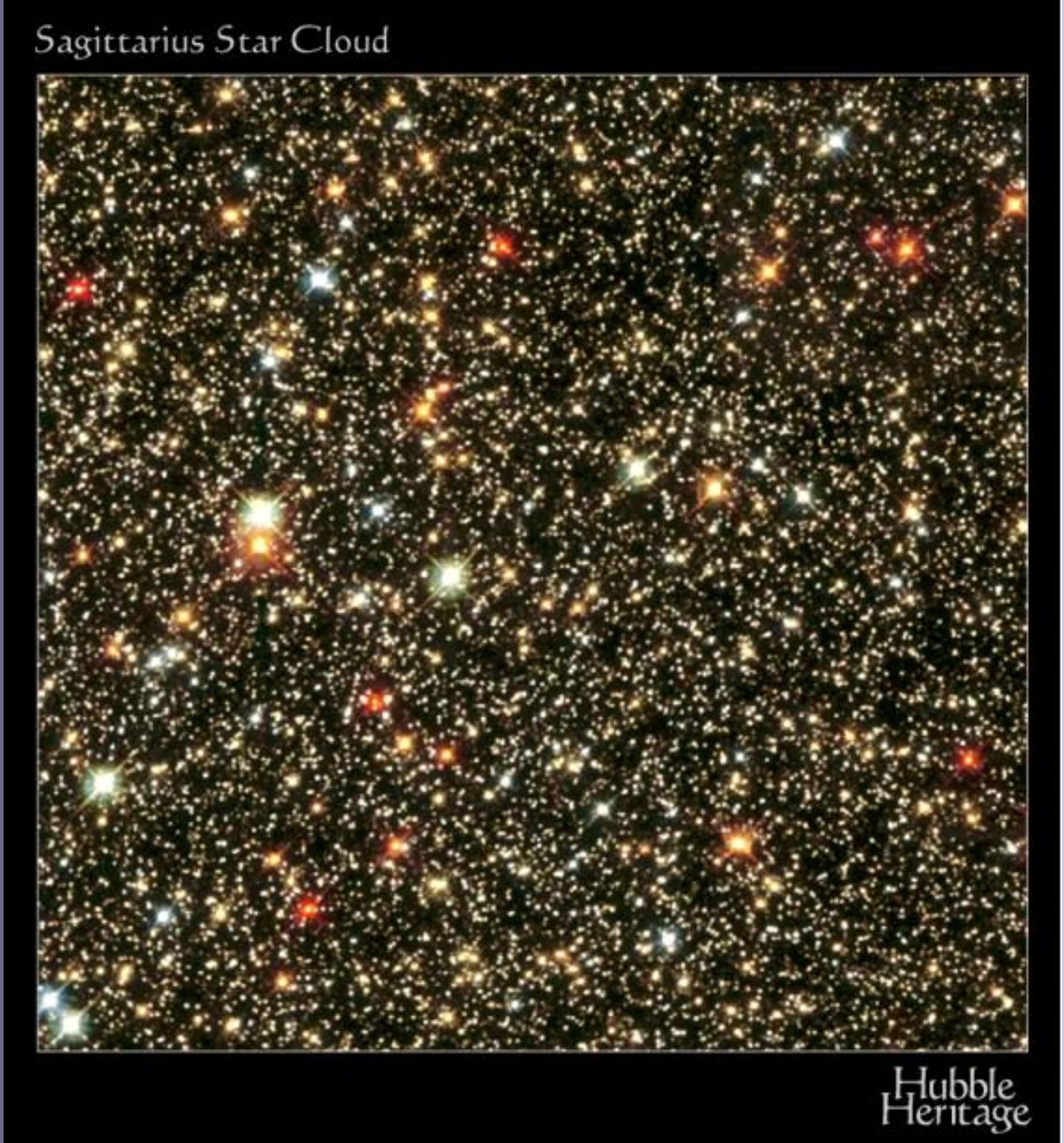
# Radio Astronomy Emission Mechanisms

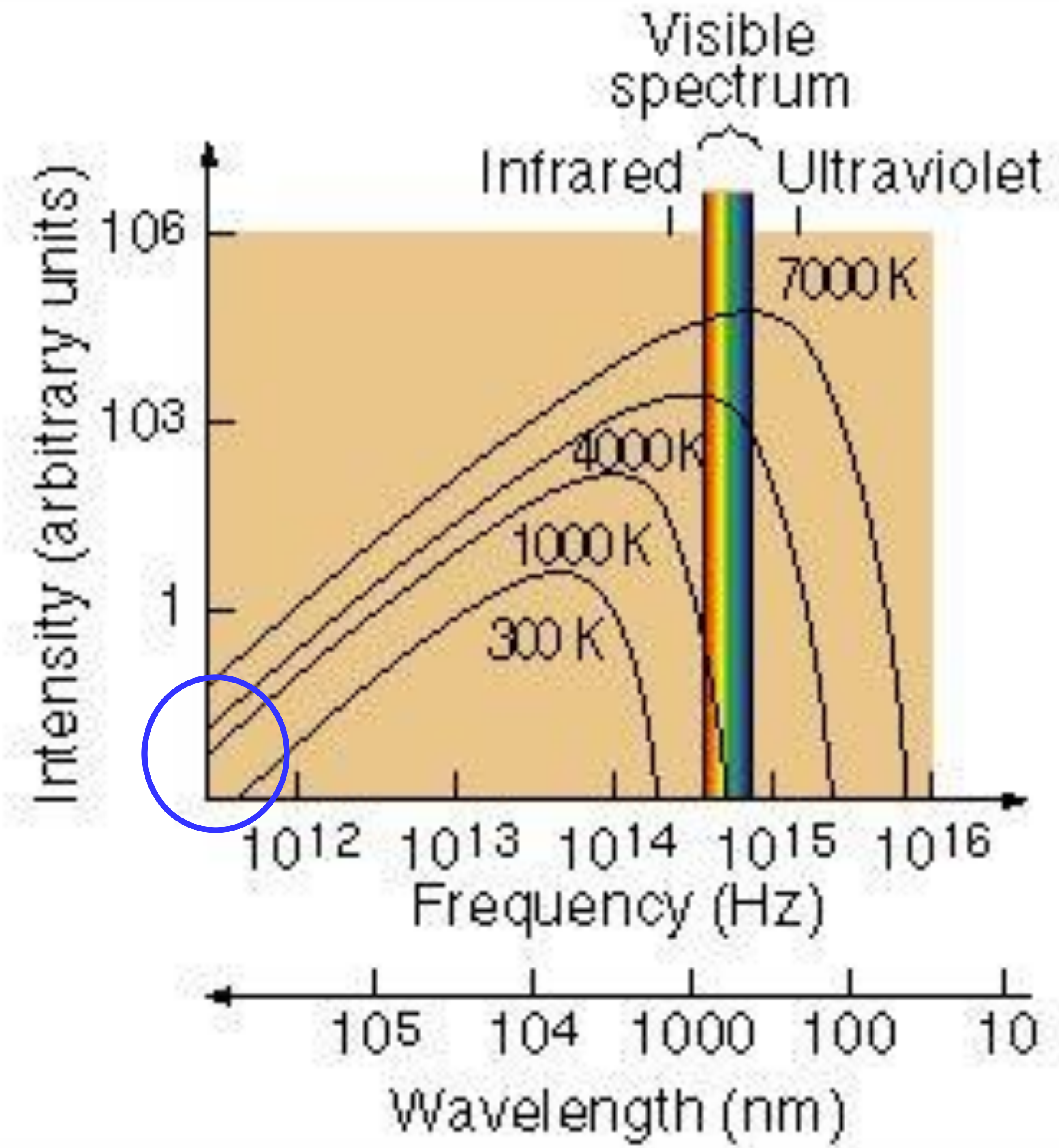



Meissa
Betelgeuse
Bellatrix
Orion
M 78
Mintaka
Alnilam
Alnitak
Orion Nebula
Rigel
Saiph

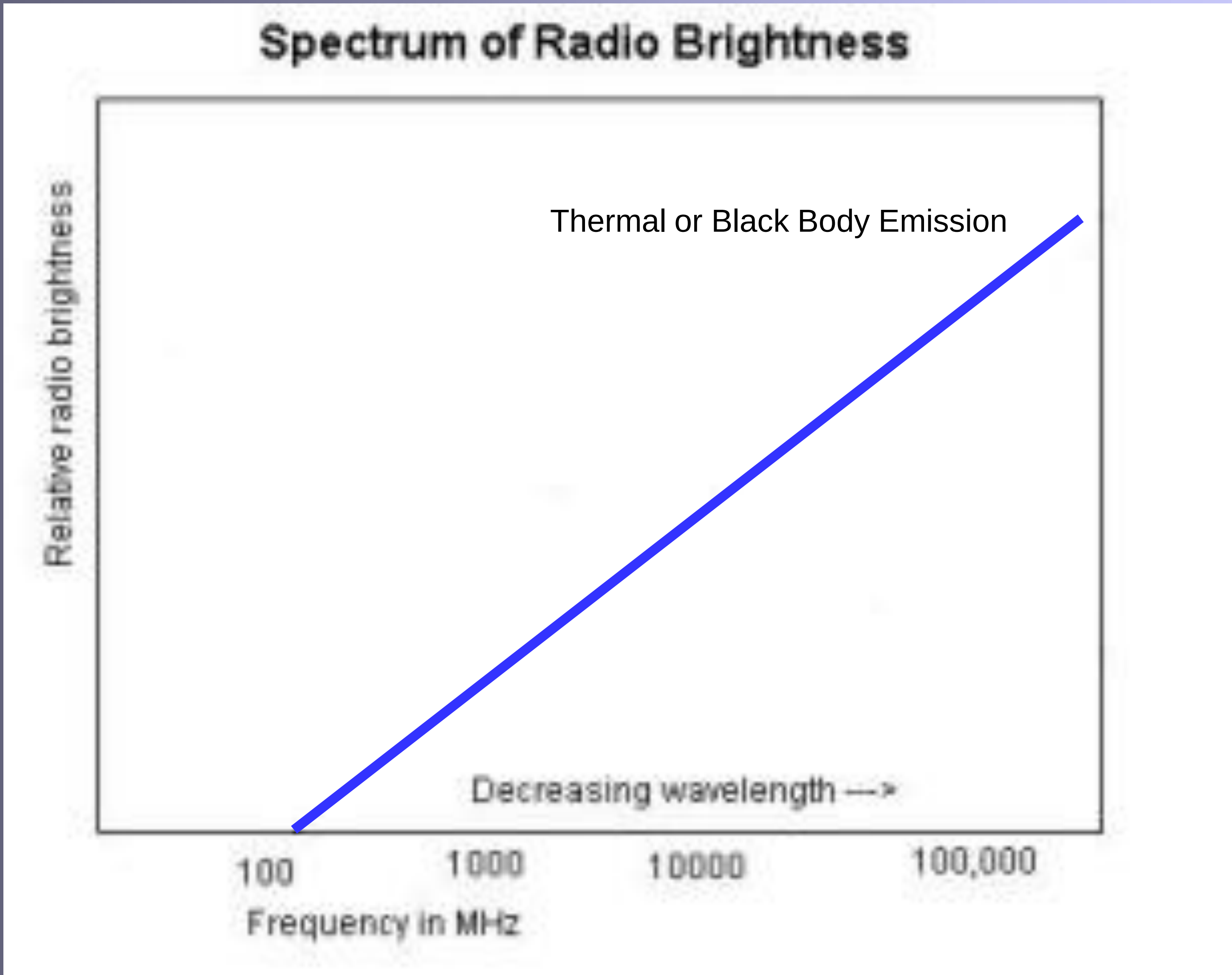
# *Recipe for Radio Waves*

Thermal Continuum Radiation
(Black Body Radiation)


Sagittarius Star Cloud
Hubble Heritage



Visible spectrum
Infrared
Ultraviolet
Intensity (arbitrary units)
106
103
1
7000 K
4000 K
1000 K
300 K
1012
1013
1014
1015
1016
Frequency (Hz)
105
104
1000
100
10
Wavelength (nm)


Spectrum of Radio Brightness
Relative radio brightness
Thermal or Black Body Emission
Decreasing wavelength --->
100
1000
10000
100,000
Frequency in MHz

# Thermal Continuum Radiation

- ***Characteristics:***
  - Opaque “Black” Body
  - Isothermal
  - In Equilibrium
- ***Planck’s Law:***
  - I = Intrinsic Intensity (ergs/cm$^2$/sec/Hz).
  - h = Planck’s Constant
  - k = Boltzman’s Constant
  - T in K

$$I = \frac{h\nu^3/c^2}{e^{h\nu/kT} - 1}$$

$$I = \frac{2\nu^2 kT}{c^2}$$

# *Recipe for Radio Waves*

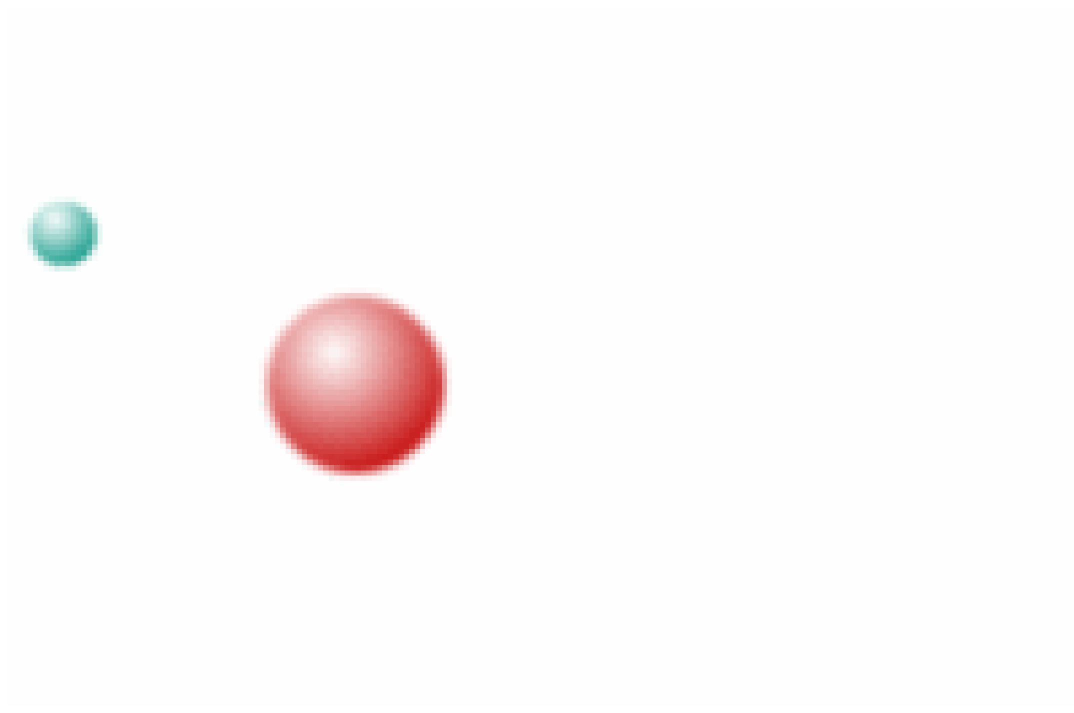
Non-Thermal Continuum Radiation

Whenever a charge particle is accelerated

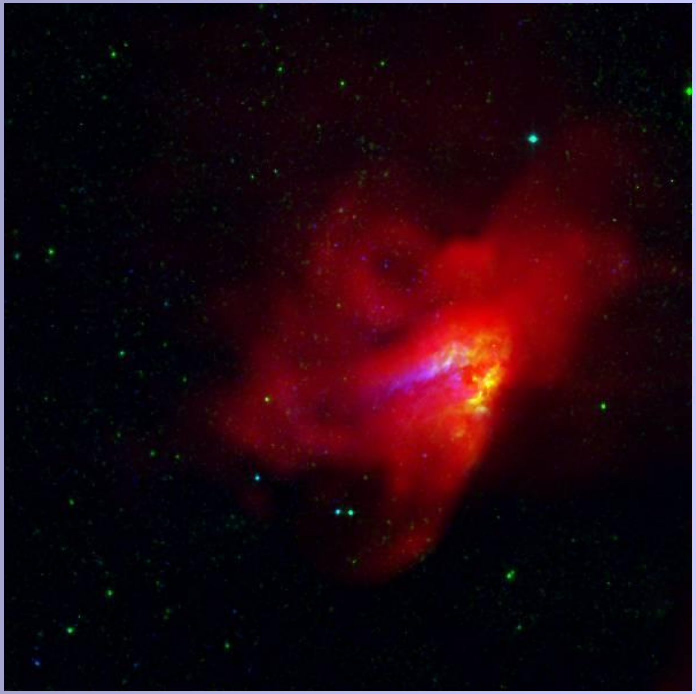
1. Free-Free Emission
   - Hot (5000 K) Ionized Gases
     - Planetary Nebulae
     - HII Regions

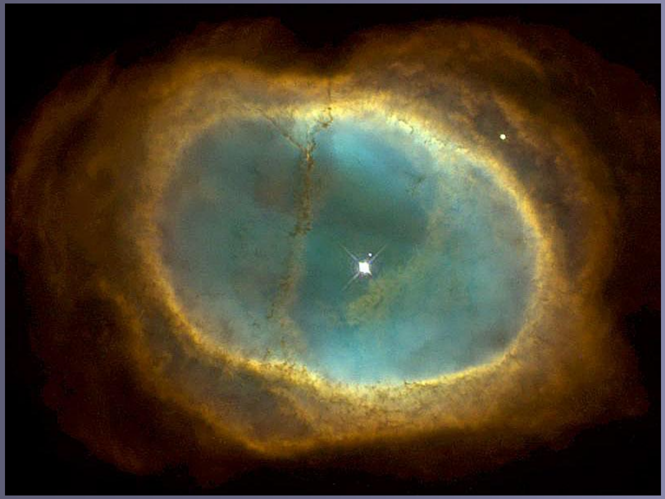
## Electron accelerates as it passes near a proton.

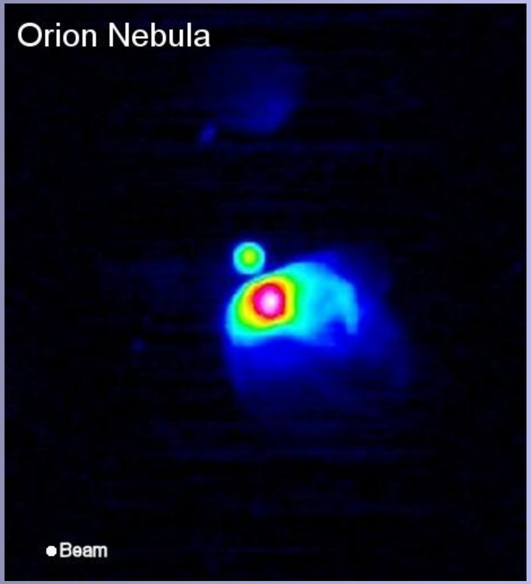
## Electromagnetic waves are released

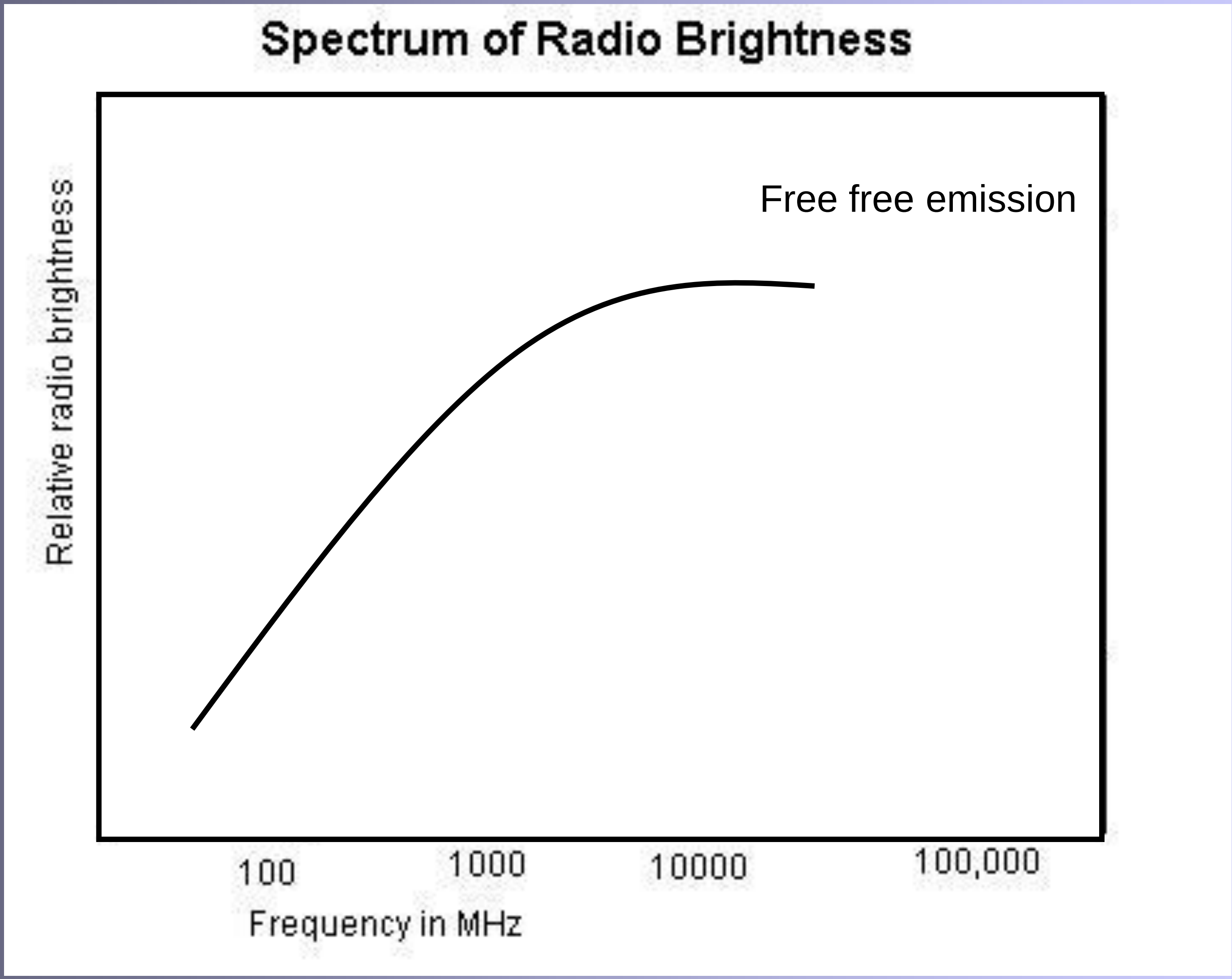


# Planetary Nebula and HII Regions









Spectrum of Radio Brightness
Free free emission
Relative radio brightness
100
1000
10000
100,000
Frequency in MHz

# Recipe for Radio Waves

***Non-Thermal Continuum Radiation***

Whenever a charge particle is accelerated

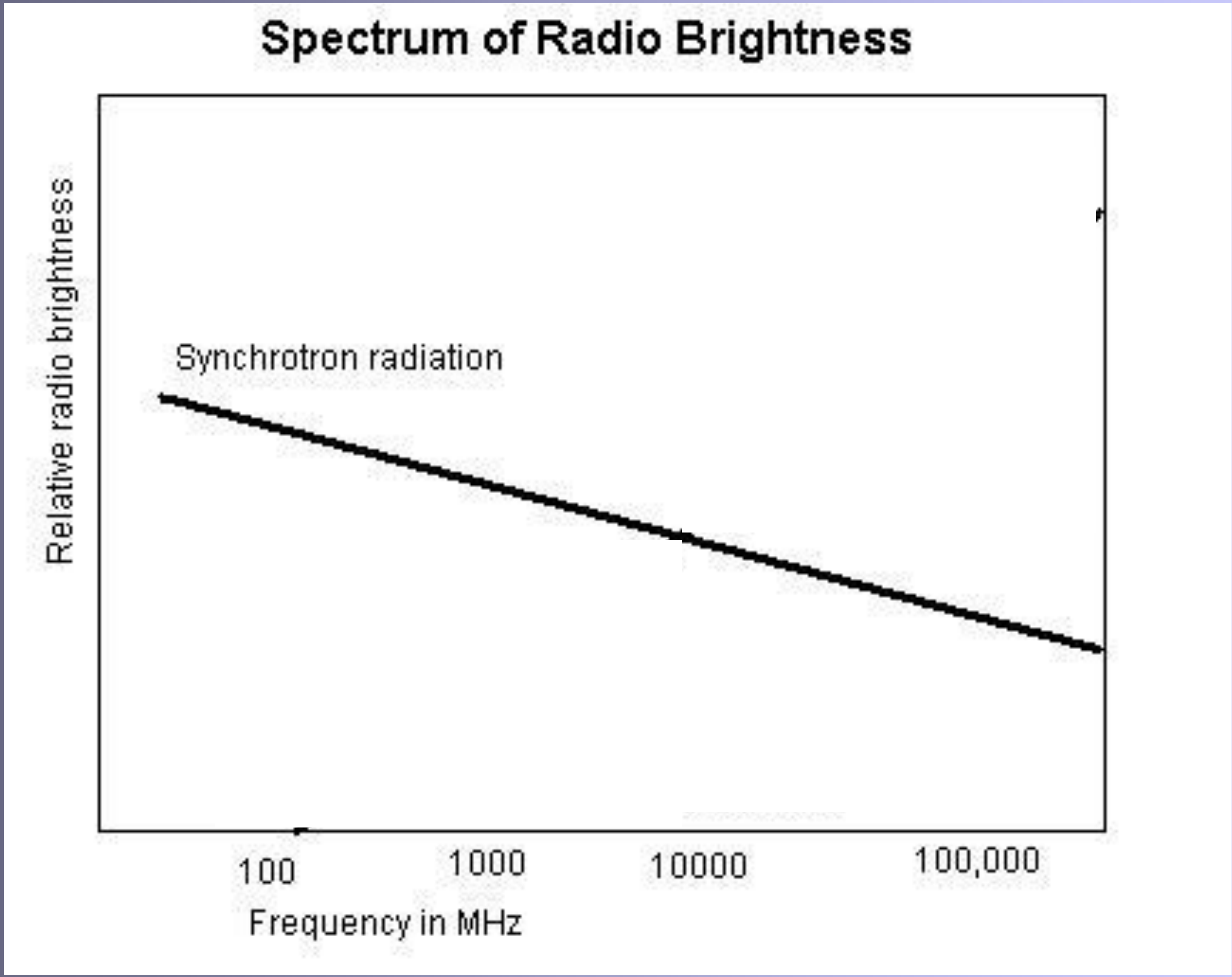
***1.Free-Free Emission***

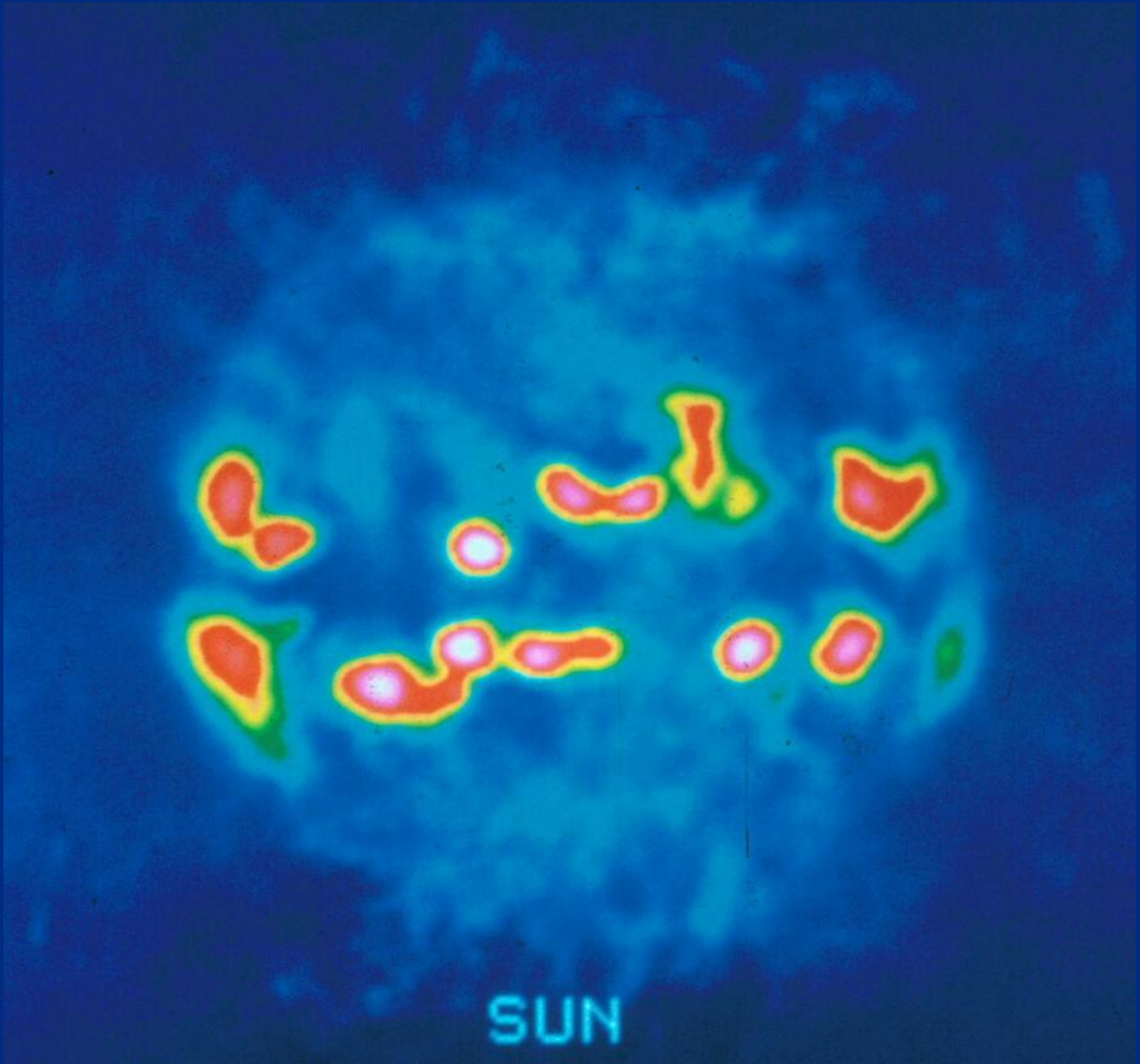
***2.Synchrotron Radiation***

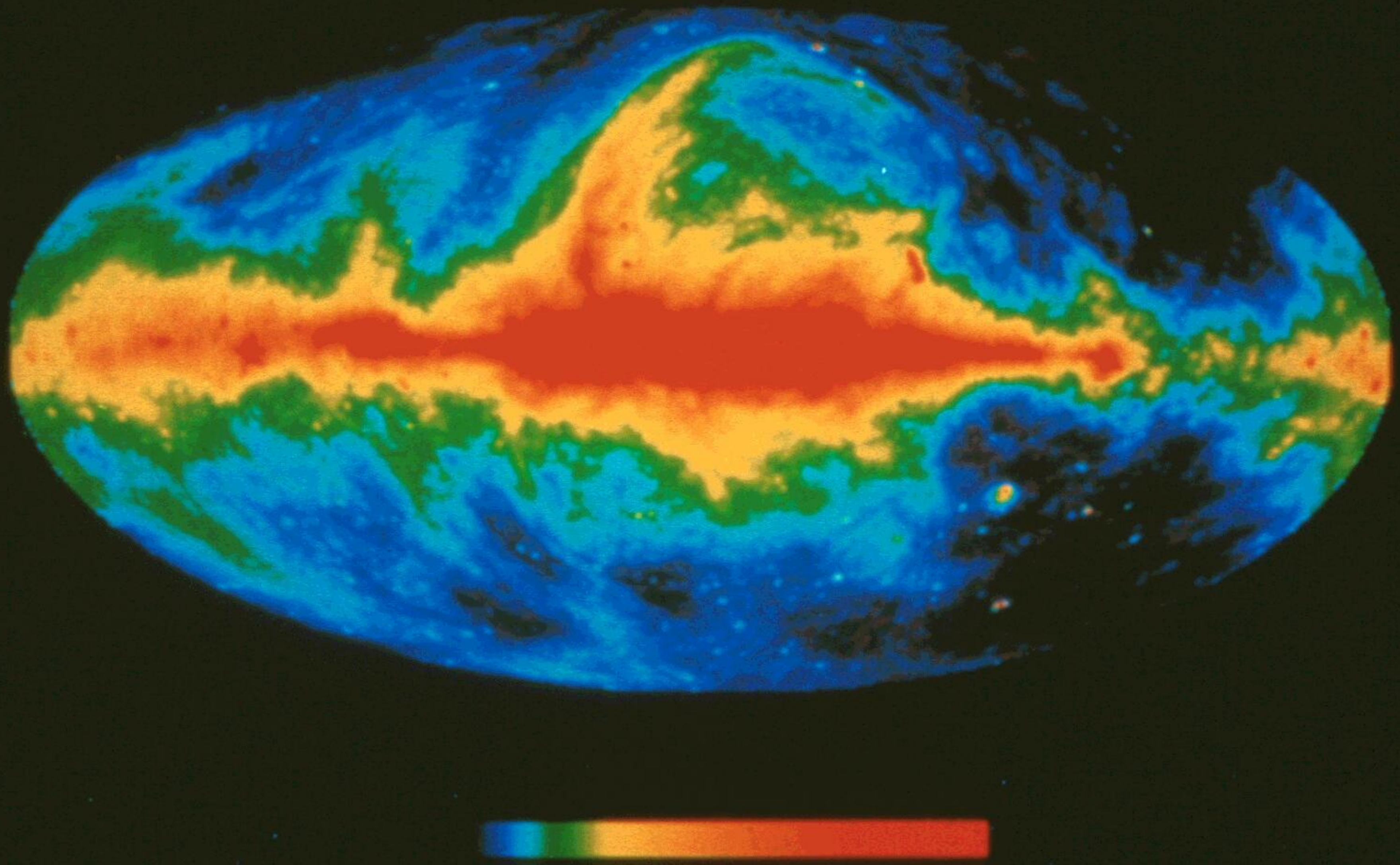
- Strong magnetic field
- Ionized gases moving at relativistic velocities

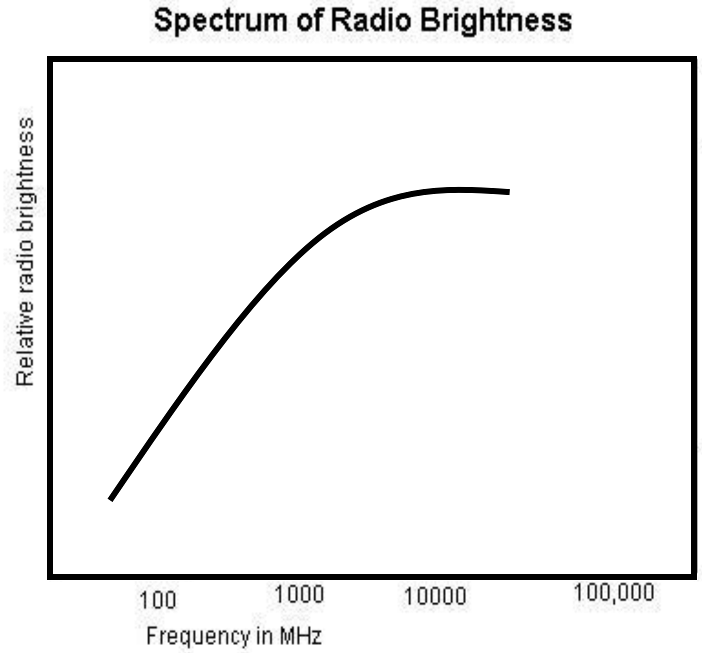
## *Electrons accelerate around magnetic field lines*

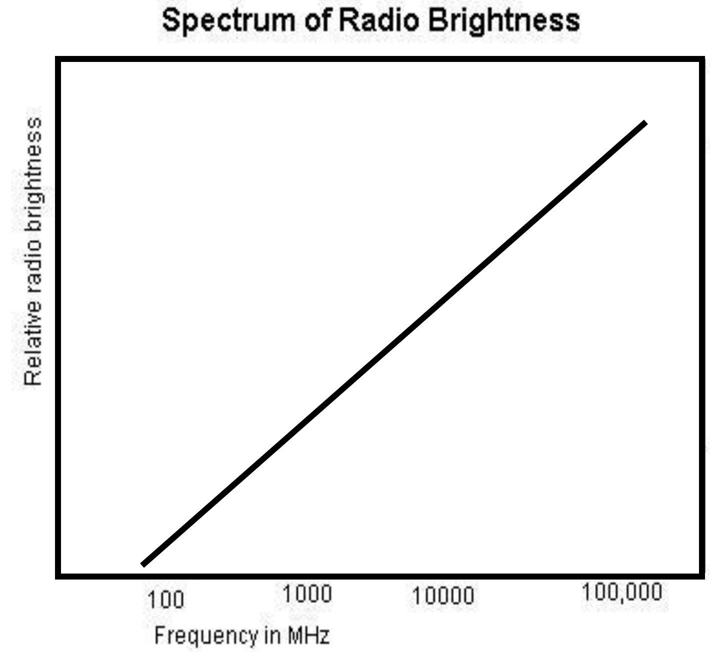
## *Electromagnetic waves are released*

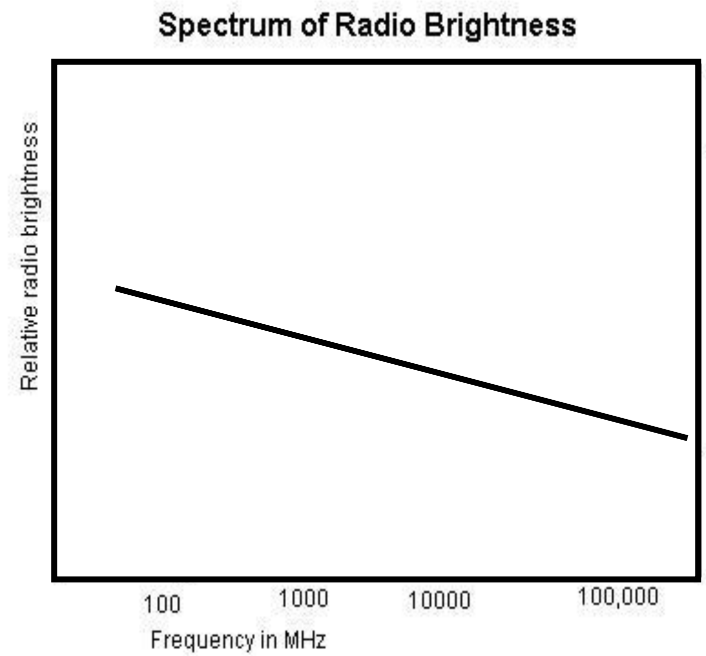

Spectrum of Radio Brightness
Relative radio brightness
Synchrotron radiation
100
1000
10000
100,000
Frequency in MHz


SUN




Spectrum of Radio Brightness
Relative radio brightness
100
1000
10000
100,000
Frequency in MHz

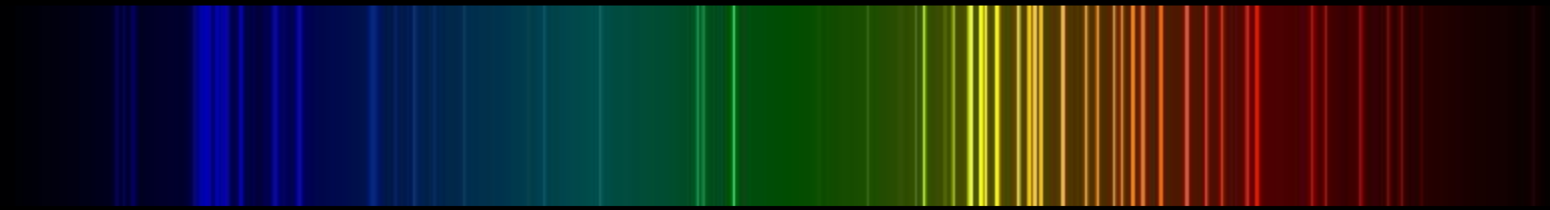

Spectrum of Radio Brightness
Relative radio brightness
100
1000
10000
100,000
Frequency in MHz


Spectrum of Radio Brightness
Relative radio brightness
100
1000
10000
100,000
Frequency in MHz

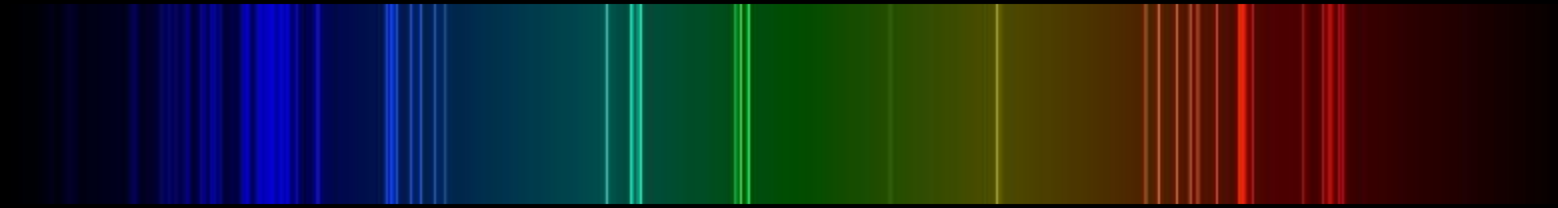
# *Recipe for Radio Waves*

## *Spectral Line Radiation*

**Atomic and molecular transitions**



Neon



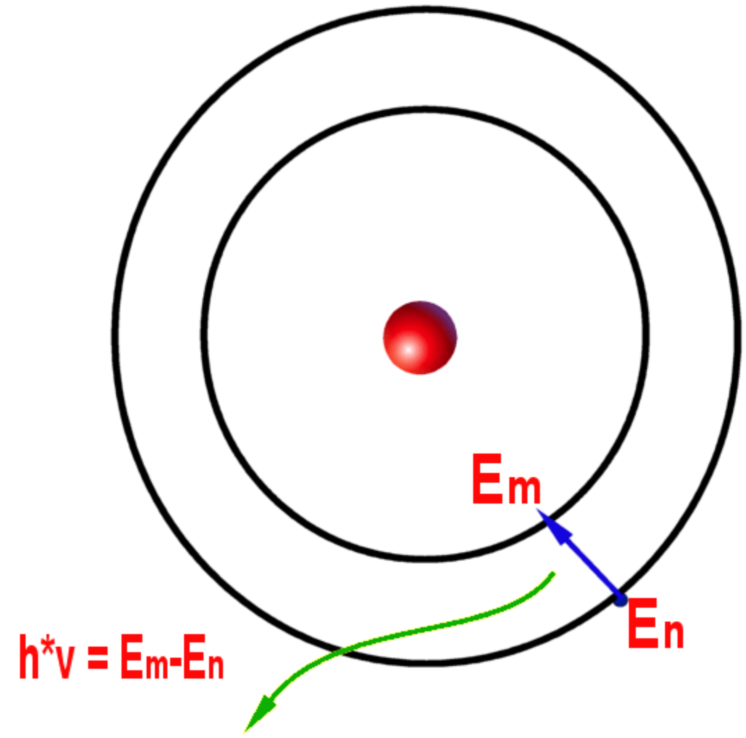
Sodium

Hydrogen

# Spectral-Line Radiation

## Recombination Lines

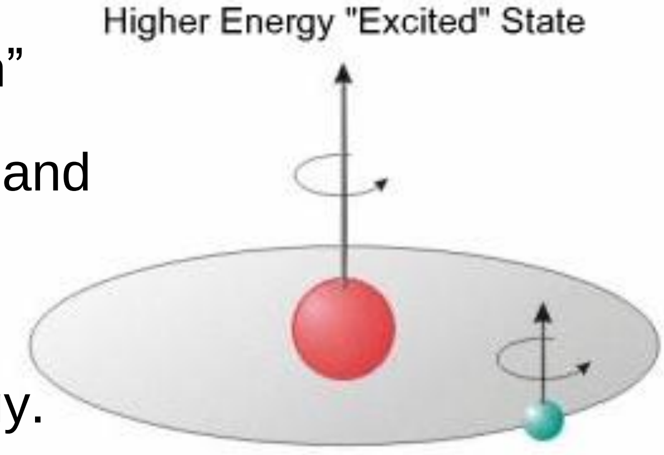
- ***Ionized regions (HII regions and planetary nebulae)***
- ***Free electrons temporarily recaptured by a proton***
- ***Atomic transitions between outer orbital (e.g., N=177 to M = 176)***

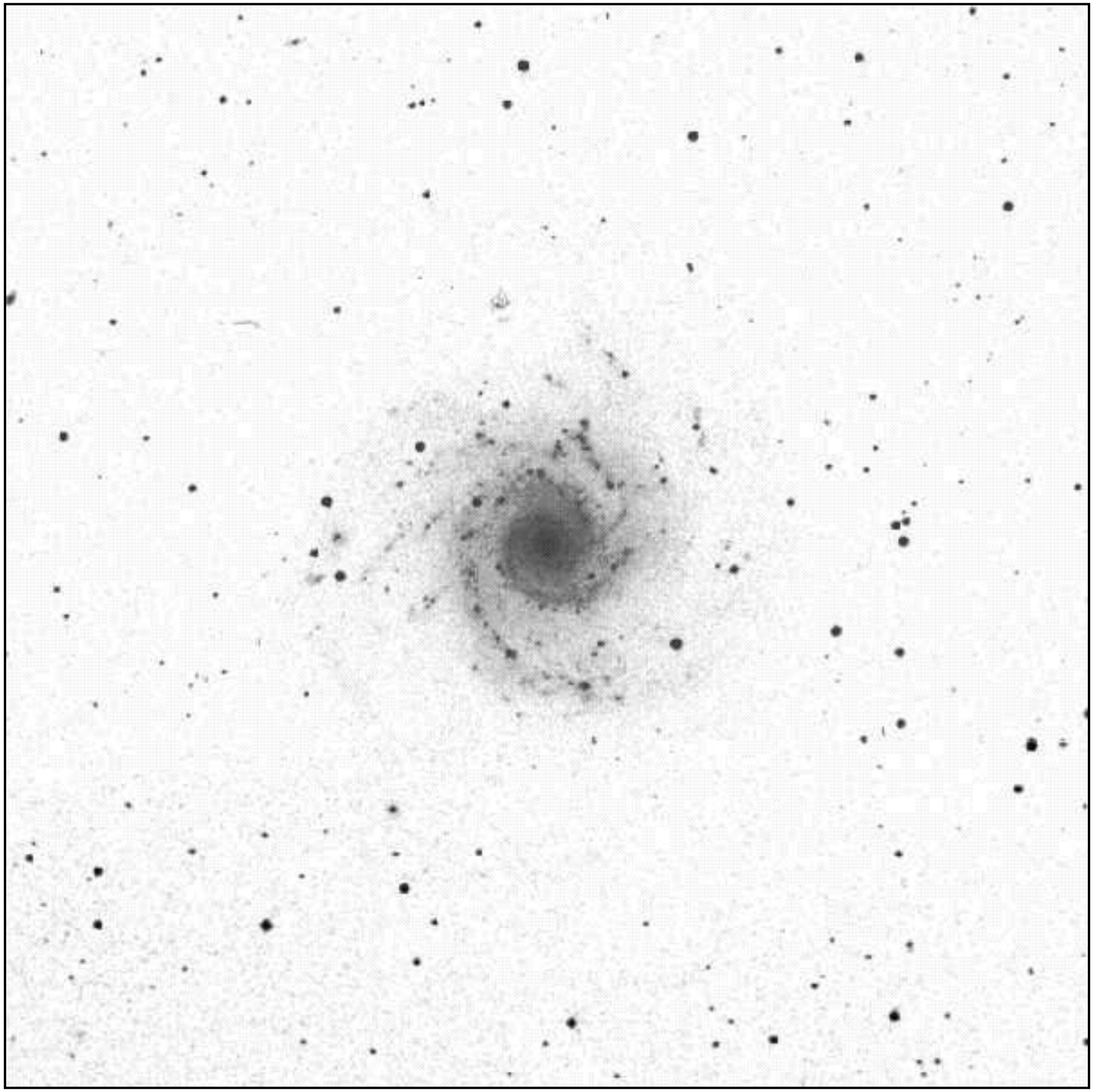


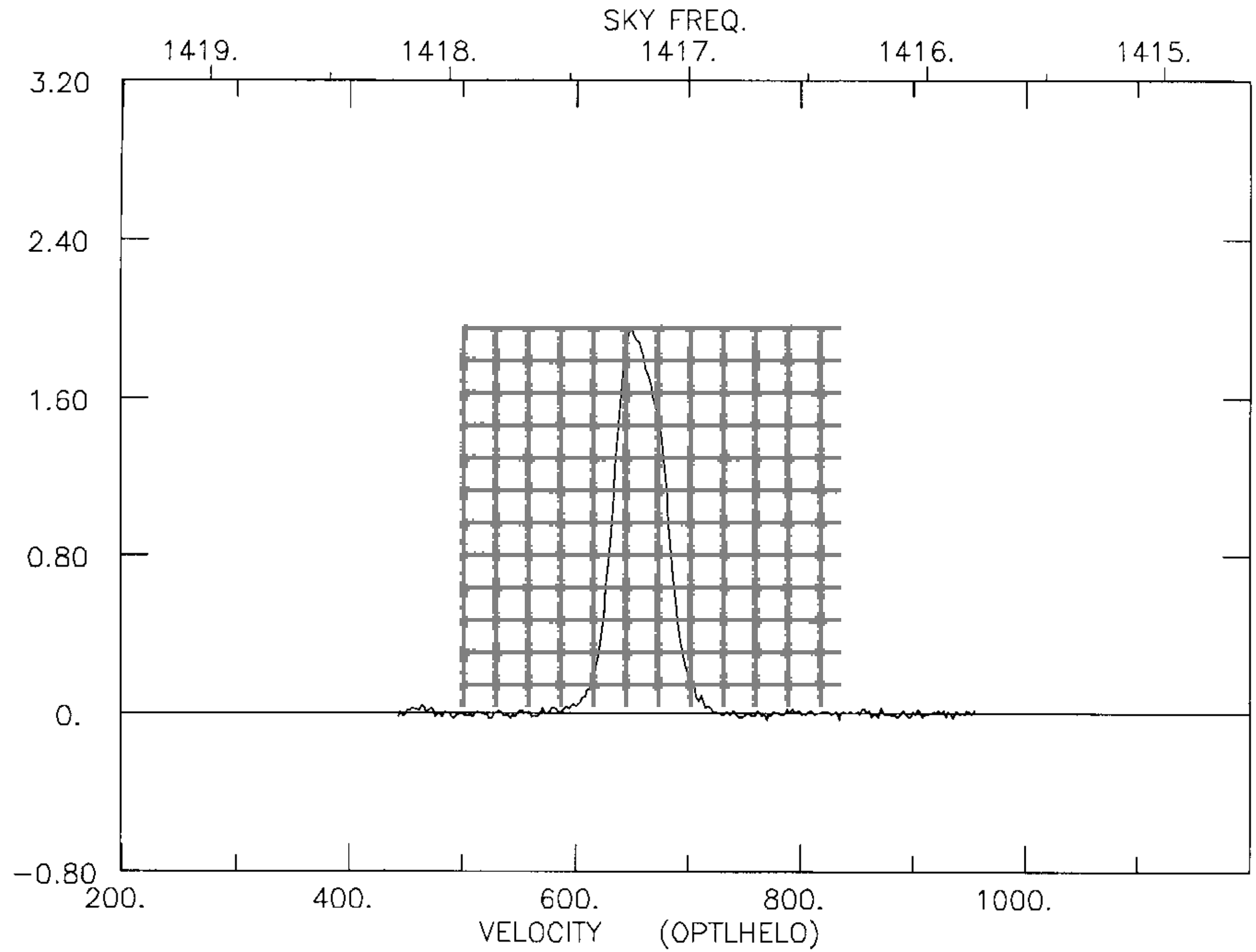

$$\nu = 3.3 \cdot 10^{15} \left( \frac{1}{m^2} - \frac{1}{n^2} \right)$$

# Hyperfine Transition of Hydrogen

- ***Found in regions where H is atomic (HI).***
- ***Spin-flip transition***
  - Electron & protons have “spin”
  - In a H atoms, spins of proton and electron may be aligned or anti-aligned.
  - Aligned state has more energy.
  - Difference in Energy = h * frequency
    - Frequency = 1420.4058 MHz
  - An aligned H atom will take 11 million years to flip
  - But, $10^{67}$ atoms in Milky Way
    - $10^{52}$ H atoms per second emit at 1420 MHz





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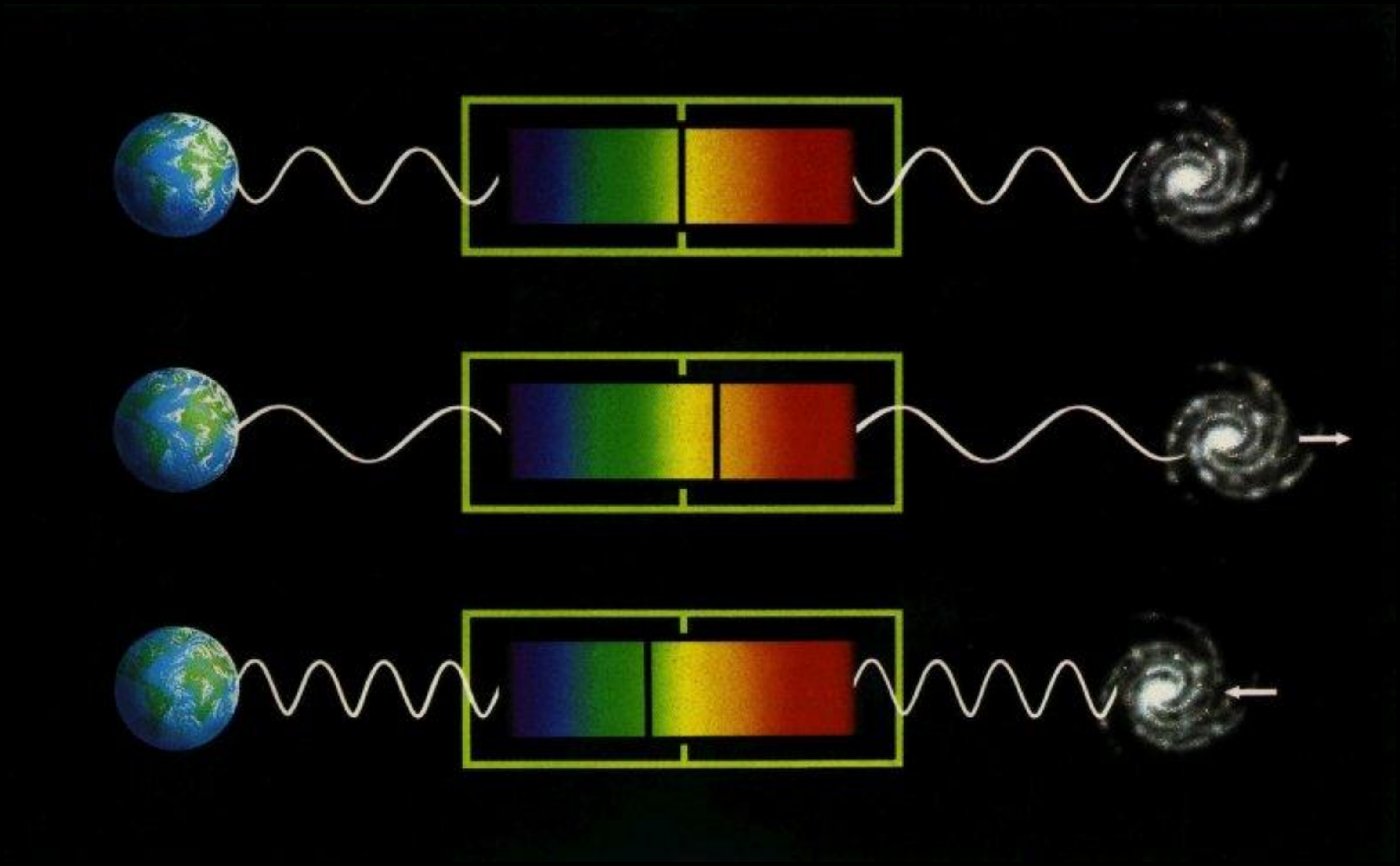
EPOCRADC=01:34: 0.6 15:31:55 CAL= 1.6 TS= 23
REST= 1420.40580 SKY= 1418.18395 IF=249.99 DFREQ= 9.766E−03 DV= 2.1

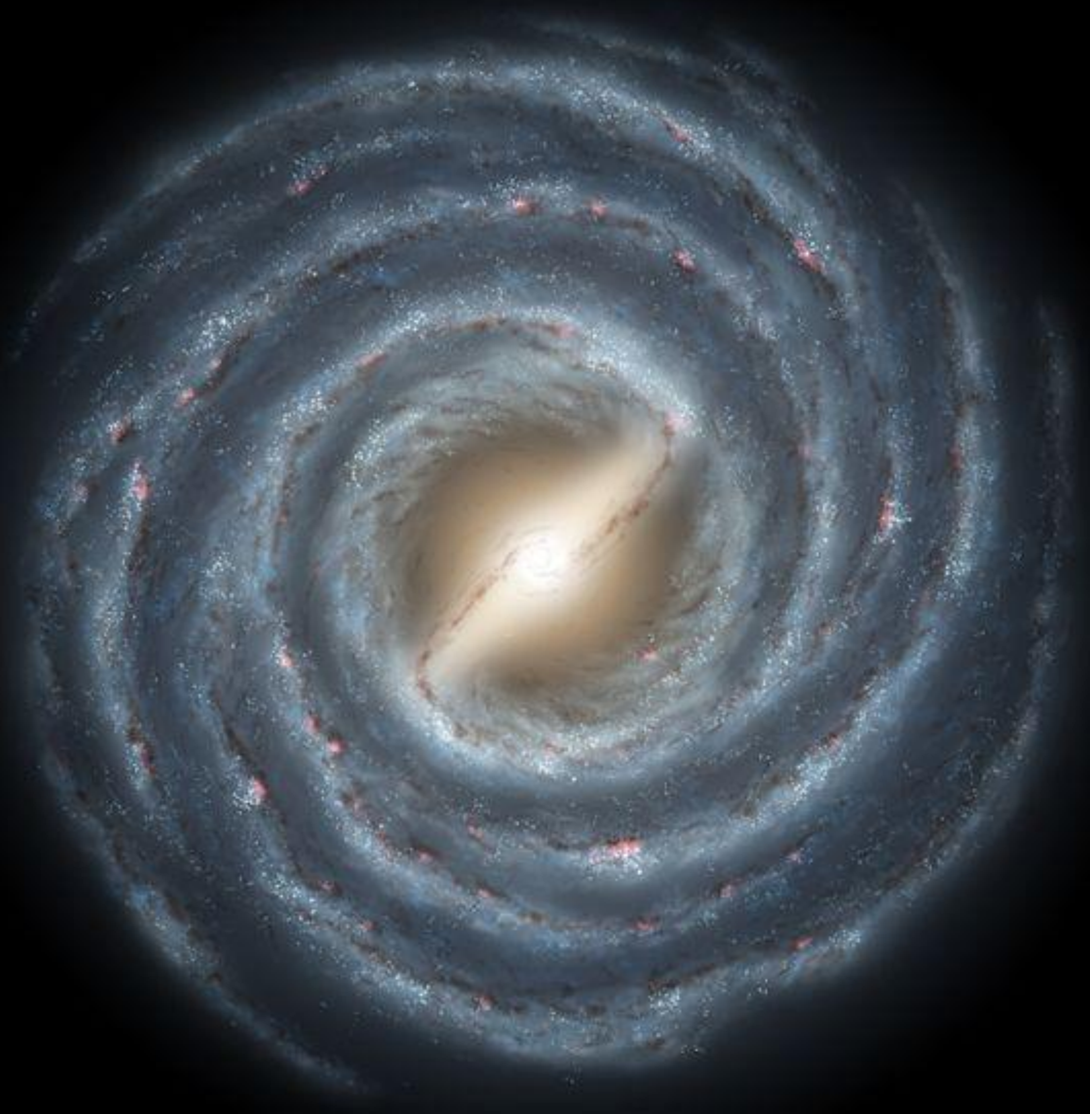
# Doppler Shift



# Doppler Shift

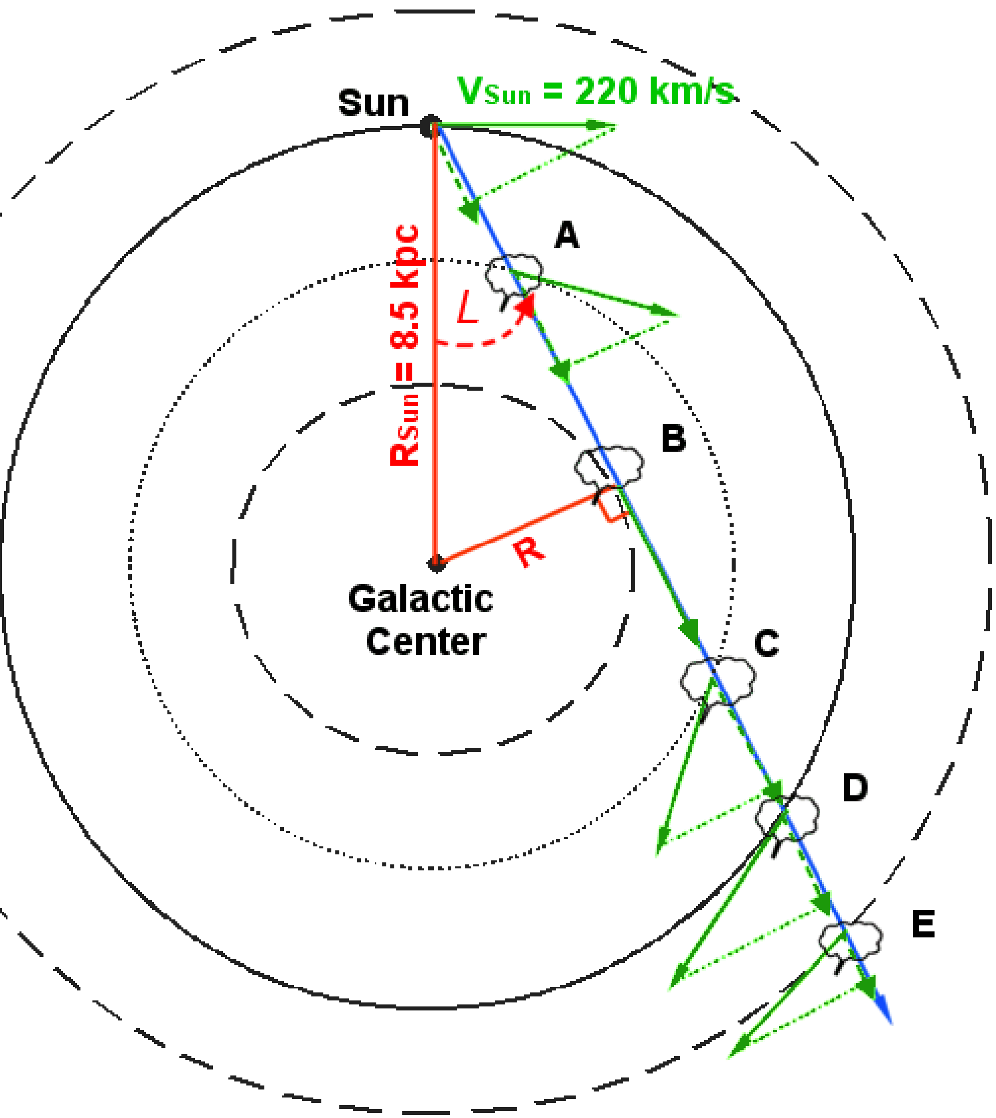
$$\text{Velecity} = c \cdot \frac{\text{RestFrequency} - \text{ObservedFrequency}}{\text{RestFrequency}}$$

- c = speed of light = 3 x $10^5$ km/sec
- Rest Frequency = 1420.4058 MHz for the hyperfine transition of Hydrogen
- If V > 0, object is moving away from us
- If V < 0, object is moving toward us.



# Spectral-Line Radiation

## Milky Way Rotation and Mass?




***For any cloud***

- Observed velocity = difference between projected Sun's motion and projected cloud motion.

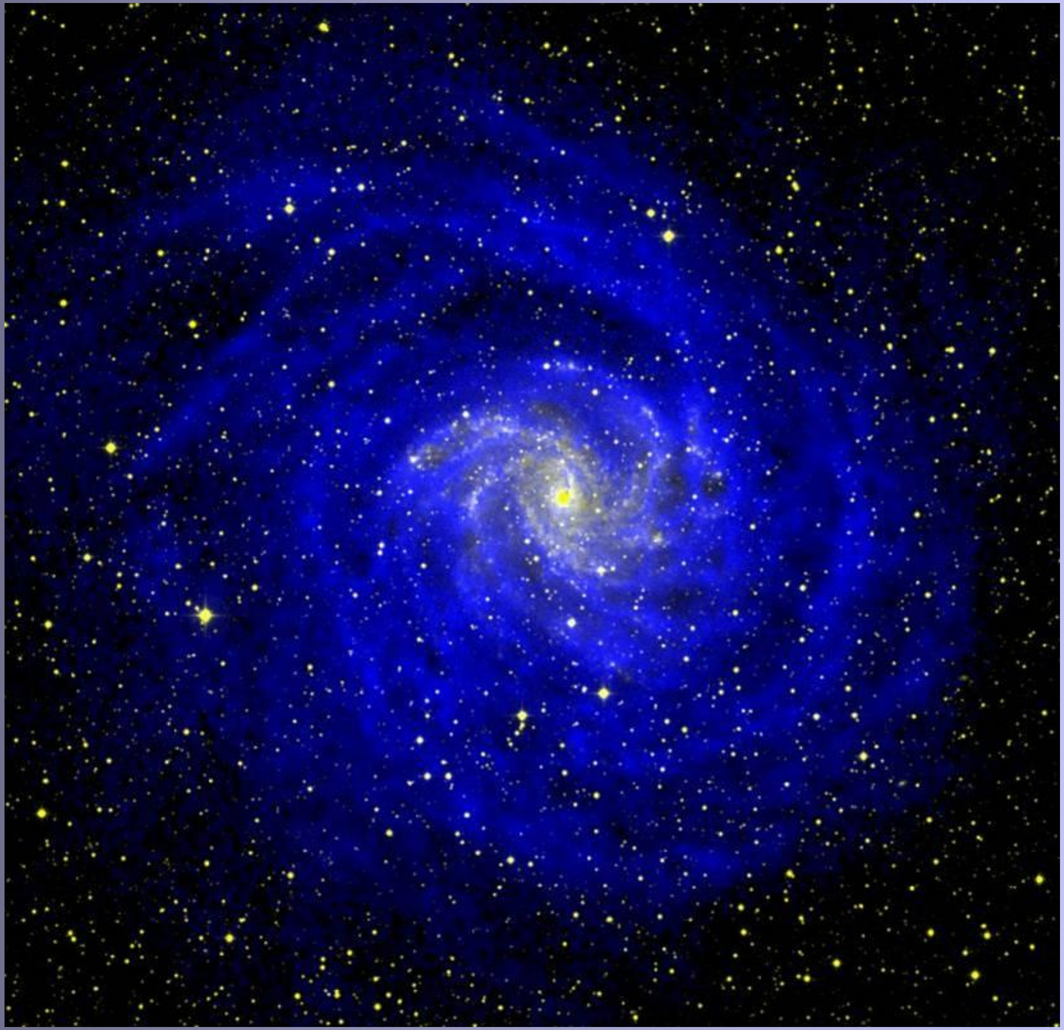
***For cloud B***

- The highest observed velocity along the line of site
- $V_{Rotation} = V_{observed} + V_{sun}*\sin(L)$
- $R = R_{Sun} * \sin(L)$

***Repeat for a different angle L and cloud B***

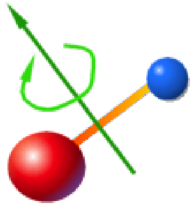
- Determine $V_{Rotation}(R)$
- From Newton's law, derive M(R) from V(R)

# Missing Mass



# Interstellar Molecules

- ***About 90% of the over 140 interstellar molecules discovered with radio telescopes.***
- ***Rotational (electric dipole) Transitions***



- ***Up to thirteen atoms***
- ***Many carbon-based (organic)***
- ***Many cannot exist in normal laboratories (e.g., OH)***
- ***$H_2$ most common molecule:***
  - No dipole moment so no radio transition.
  - Only observable in UV (rotational) or Infrared (vibrational) transitions.
  - Astronomers use CO as a tracer for $H_2$
- ***A few molecules (OH, $H_2O$, …) maser***

| *Chemical symbol* | *Name of molecule* | *Year of discovery* | *Part of spectrum* |
|---|---|---|---|
| *Two atoms* | | | |
| CH | methylidyne | 1937 | visible |
| CN | cyanogen radical | 1940 | visible |
| $CH^+$ | methyladyne ion | 1941 | visible |
| OH | hydroxyl radical | 1963 | radio |
| CO | carbon monoxide | 1970 | radio |
| $H_2$ | molecular hydrogen | 1970 | ultraviolet |
| CS | carbon monosulfide | 1971 | radio |
| SiO | silicon monoxide | 1971 | radio |
| SO | sulfur monoxide | 1973 | radio |
| NS | nitrogen sulfide radical | 1975 | radio |
| SiS | silicon sulfide | 1975 | radio |
| $C_2$ | diatomic carbon | 1977 | infrared |
| NO | nitric oxide | 1978 | radio |
| HCl | hydrogen chloride | 1984 | infrared |
| PN | phosphorus nitride | 1987 | radio |
| NaCl | sodium chloride | 1987 | radio |
| AlCl | aluminum chloride | 1987 | radio |
| KCl | potassium chloride | 1987 | radio |
| AlF | aluminum fluoride | 1987 | radio |
| SiC | silicon carbide | 1989 | radio |
| CP | phosphorus carbide | 1989 | radio |
| SiN | silicon nitride | 1990 | radio |
| NH | nitrogen hydride | 1991 | ultraviolet |
| *Three atoms* | | | |
| $H_2O$ | water | 1968 | radio |
| $HCO^+$ | formyl ion | 1970 | radio |
| HCN | hydrogen cyanide | 1970 | radio |
| HNC | hydrogen isocyanide | 1971 | radio |
| OCS | carbonyl sulfide | 1971 | radio |
| HS | hydrogen sulfide | 1972 | radio |
| $C_2H$ | ethynyl radical | 1974 | radio |
| $N_2H^+$ | diazenylium | 1974 | radio |
| $SO_2$ | sulfur dioxide | 1975 | radio |
| HCO | formyl radical | 1976 | radio |
| HNO | nitroxyl radical | 1977 | radio |
| $HCS^+$ | thioformylium | 1980 | radio |
| $SiC_2$ | silicon dicarbide | 1984 | radio |
| $H_2D^+$ | (unnamed) | 1985 | infrared |
| $C_2S$ | (unnamed) | 1986 | radio |
| $SiH_2$ | silylene (unconfirmed) | 1990 | radio |
| $C_2O$ | dicarbon monoxide | 1991 | radio |
| *Four atoms* | | | |
| $NH_3$ | ammonia | 1968 | radio |
| $H_2CO$ | formaldehyde | 1969 | radio |
| HNCO | isocyanic acid | 1971 | radio |
| $H_2CS$ | thioformaldehyde | 1971 | radio |
| $C_2H_2$ | acetylene | 1976 | infrared |
| $C_3N$ | cyanoethynyl radical | 1976 | radio |
| HNCS | isothiocyanic acid | 1979 | radio |
| $HOCO^+$ | protonated carbon dioxide | 1980 | radio |
| $C_3H$ | propynylidyne | 1984 | radio |
| $C_3O$ | tricarbon monoxide | 1984 | radio |
| $HCNH^+$ | protonated HCN | 1984 | radio |
| $H_3O^+$ | protonated water | 1986 | radio |
| $C_3S$ | tricarbon monosulfide | 1986 | radio |
| HCCN | (unnamed) | 1991 | radio |
| *Five atoms* | | | |
| HCOOH | formic acid | 1970 | radio |
| $HC_3N$ | cyanoacetylene | 1970 | radio |
| $CH_2NH$ | methanimine | 1972 | radio |
| $NH_2CN$ | cyanamide | 1975 | radio |
| $H_2CCO$ | ketene | 1976 | radio |
| $C_4H$ | butadiynyl radical | 1978 | radio |
| $CH_4$ | methane | 1978 | radio |
| $SiH_4$ | silane | 1984 | infrared |
| $C_3H_2$ | cyclopropenylidene | 1985 | radio |
| $CH_2CN$ | cyanomethyl radical | 1987 | radio |
| $C_4Si$ | (unnamed) | 1989 | radio |
| $H_2C_3$ | propadienylidene | 1990 | radio |
| *Six atoms* | | | |
| $CH_3OH$ | methyl alcohol | 1970 | radio |
| $CH_3CN$ | methyl cyanide | 1971 | radio |
| $NH_2CHO$ | formamide | 1971 | radio |
| $CH_3SH$ | methyl mercaptan | 1979 | radio |
| $C_2H_4$ | ethylene | 1980 | infrared |
| $C_5H$ | pentynylidyne radical | 1986 | radio |
| $CH_3NC$ | methyl isocyanide | 1987 | radio |
| HCCCHO | propynal | 1989 | radio |
| $H_2C_4$ | butatrienylidene | 1990 | radio |
| *Seven atoms* | | | |
| $CH_3C_2H$ | methylacetylene | 1971 | radio |
| $CH_3CHO$ | acetaldehyde | 1971 | radio |
| $CH_3NH_2$ | methylamine | 1974 | radio |
| $CH_2CHCN$ | vinyl cyanide | 1975 | radio |
| $HC_5N$ | cyanodiacetylene | 1976 | radio |
| $C_6H$ | hexatriynyl radical | 1986 | radio |
| *Eight atoms* | | | |
| $CH_3OHCO$ | methyl formate | 1975 | radio |
| $CH_3C_3N$ | methyl cyanoacetylene | 1983 | radio |
| *Nine atoms* | | | |
| $CH_3CH_2OH$ | ethyl alcohol (ethanol) | 1974 | radio |
| $(CH_3)_2O$ | dimethyl ether | 1974 | radio |
| $CH_3CH_2CN$ | ethyl cyanide | 1977 | radio |
| $HC_7N$ | cyanotriacetylene | 1977 | radio |
| $CH_3C_4H$ | methyl diacetylene | 1984 | radio |
| *Ten atoms* | | | |
| $(CH_3)_2CO$ | acetone (unconfirmed) | 1987 | radio |
| *Eleven atoms* | | | |
| $HC_9N$ | cyano-octatetrayne | 1977 | radio |
| *Thirteen atoms* | | | |
| $HC_{11}N$ | cyanotetracetylene | 1981 | radio |

*Six atoms*

| | | | |
|---|---|---|---|
| $CH_3OH$ | methyl alcohol | 1970 | radio |
| $CH_3CN$ | methyl cyanide | 1971 | radio |
| $NH_2CHO$ | formamide | 1971 | radio |
| $CH_3SH$ | methyl mercaptan | 1979 | radio |
| $C_2H_4$ | ethylene | 1980 | infrared |
| $C_5H$ | pentynylidyne radical | 1986 | radio |
| $CH_3NC$ | methyl isocyanide | 1987 | radio |
| HCCCHO | propynal | 1989 | radio |
| $H_2C_4$ | butatrienylidene | 1990 | radio |

*Seven atoms*

| | | | |
|---|---|---|---|
| $CH_3C_2H$ | methylacetylene | 1971 | radio |
| $CH_3CHO$ | acetaldehyde | 1971 | radio |
| $CH_3NH_2$ | methylamine | 1974 | radio |
| $CH_2CHCN$ | vinyl cyanide | 1975 | radio |
| $HC_5N$ | cyanodiacetylene | 1976 | radio |
| $C_6H$ | hexatriynyl radical | 1986 | radio |

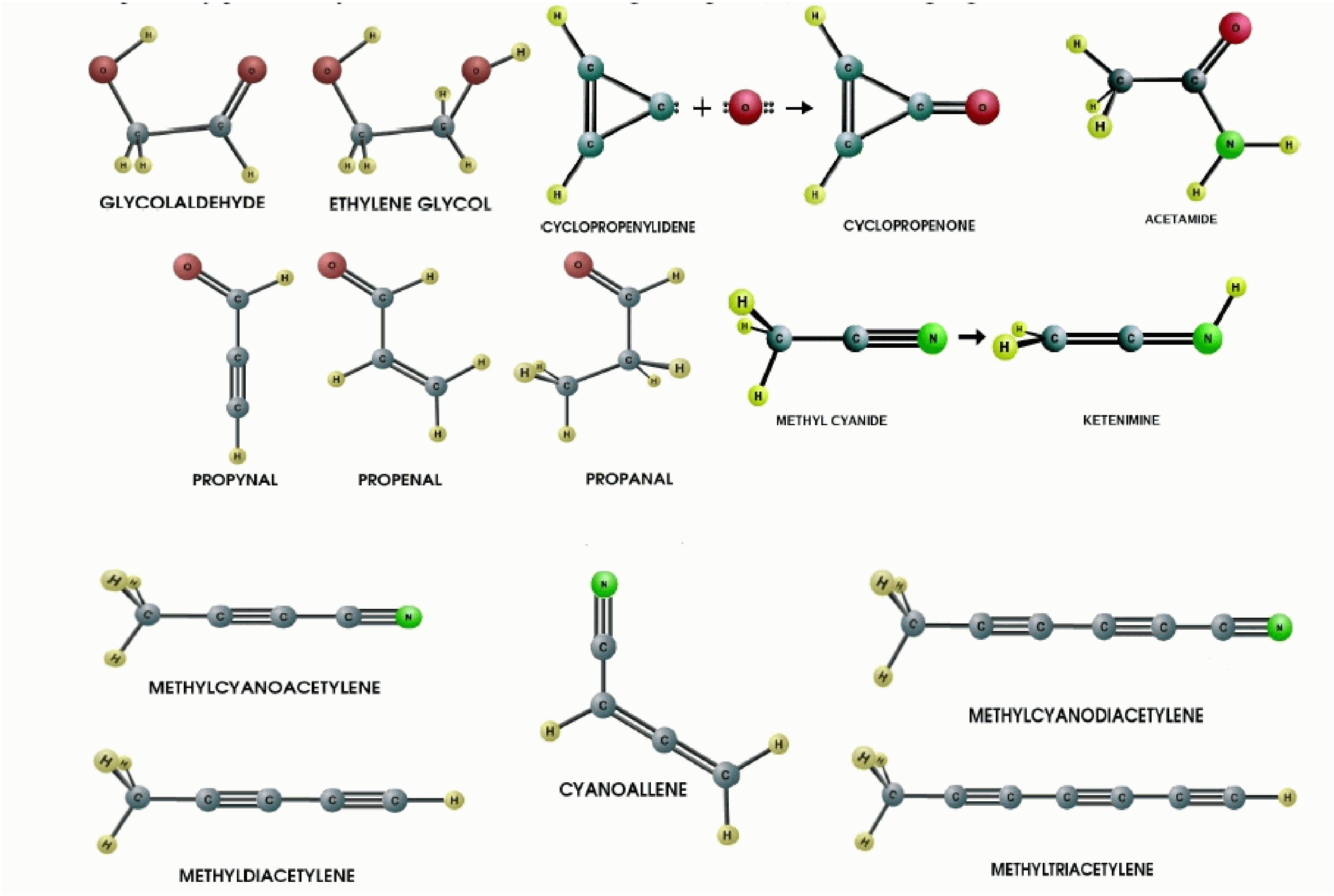
*Eight atoms*

| | | | |
|---|---|---|---|
| $CH_3OHCO$ | methyl formate | 1975 | radio |
| $CH_3C_3N$ | methyl cyanoacetylene | 1983 | radio |

*Nine atoms*

| | | | |
|---|---|---|---|
| $CH_3CH_2OH$ | ethyl alcohol (ethanol) | 1974 | radio |
| $(CH_3)_2O$ | dimethyl ether | 1974 | radio |
| $CH_3CH_2CN$ | ethyl cyanide | 1977 | radio |
| $HC_7N$ | cyanotriacetylene | 1977 | radio |
| $CH_3C_4H$ | methyl diacetylene | 1984 | radio |

# Molecules Discovered by the GBT



# Discovery of Ethanol

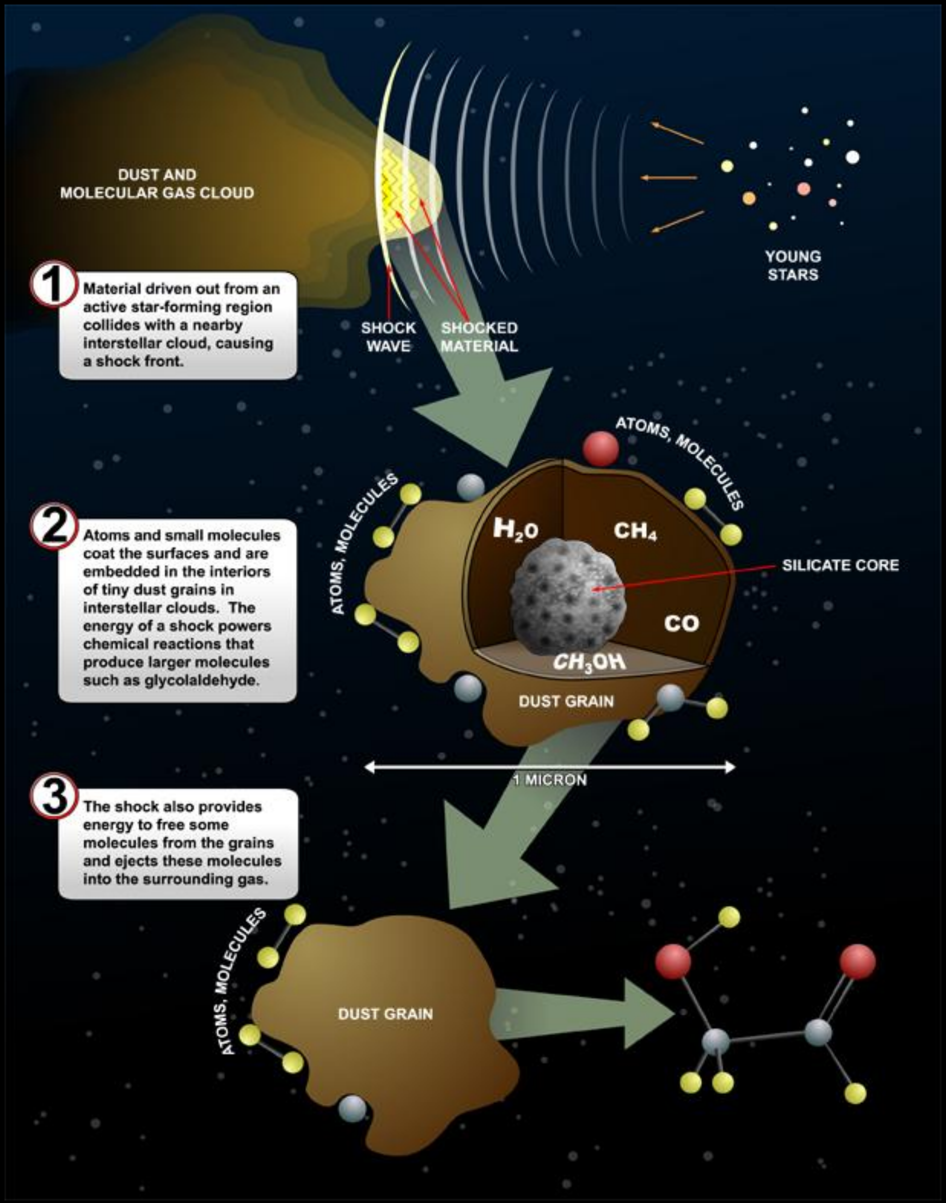
Ethyl alcohol has been of interest to mankind since the dawn of the earliest civilizations (Hallo and Simpson 1971; Seltman 1957). During early October of 1974 we detected a truly astronomical source of ethyl alcohol located in the general direction of the center of our Galaxy. Preliminary estimates indicate that the alcoholic content of this cloud (Sgr B2), if purged of all impurities and condensed, would yield approximately $10^{28}$ fifths at 200 proof. This exceeds the total amount of all of man's fermentation efforts since the beginning of recorded history.

In the laboratory, ethyl alcohol exists in the *trans* and *gauche* conformations (Sasada *et al*. 1971) although it is uncertain which is the most stable (lowest energy) form. Figure 1 shows a simplified diagram of the configurations of the atoms in the *trans* and *gauche* con-

# Interstellar Molecule Formation

- ***Need high densities (100 –$10^6$ H atoms/$cm^3$)***
  - Lots of dust needed to protect molecules for stellar UV
    - Form in dust clouds = Molecular Clouds
    - Associated with stars formation
  - But, optically obscured – need radio telescopes
- ***Low temperatures (< 100 K)***
- ***Some molecules (e.g., $H_2$) form on dust grains***
- ***Most form via ion-molecular gas-phase reactions***
  - Exothermic
  - Charge transfer

# Grain Chemistry



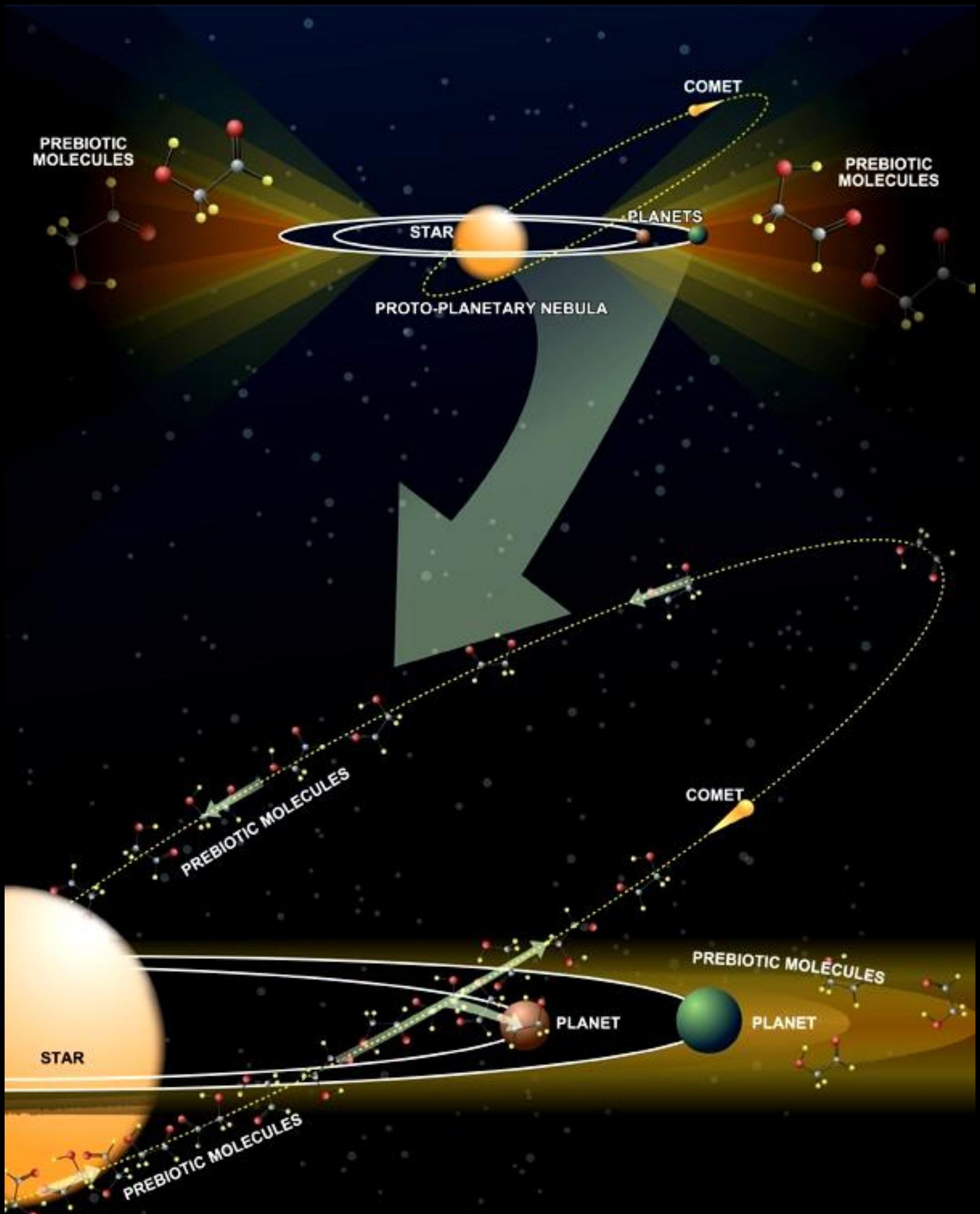
# Ion-molecular gas-phase reactions

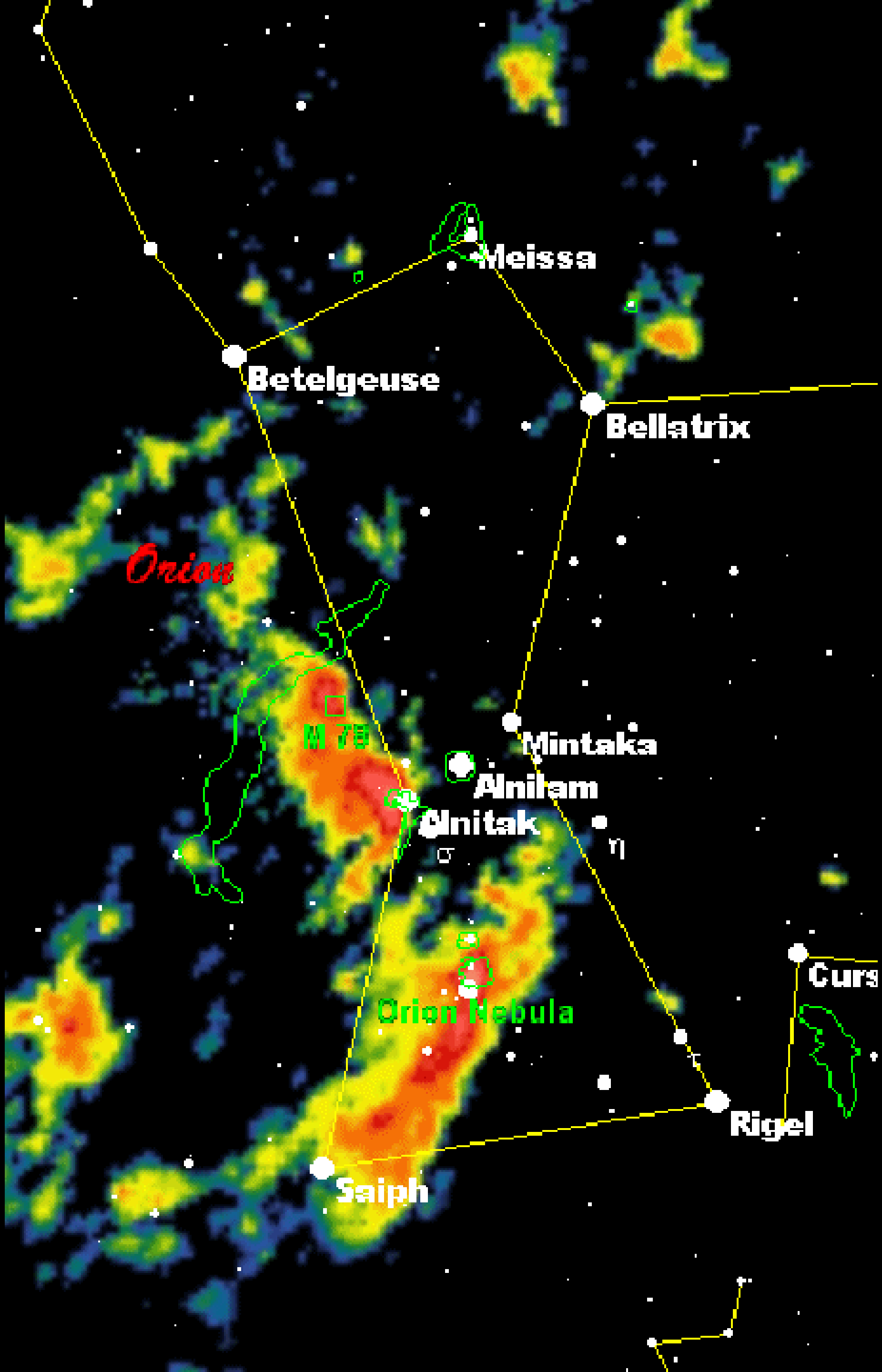
## Examples of types of reactions

| | |
|---|---|
| $C^+ + H_2 \rightarrow CH_2^+ + h\nu$ | (Radiative Association) |
| $H_2^+ + H_2 \rightarrow H_3^+ + H$ | (Dissociative Charge Transfer) |
| $H_3^+ + CO \rightarrow HCO^+ + H_2$ | (Proton Transfer) |
| $H_3^+ + Mg \rightarrow Mg^+ + H_2 + H$ | (Charge Transfer) |
| $He^+ + CO \rightarrow He + C^+ + O$ | (Dissociative Charge Transfer) |
| $HCO^+ + e \rightarrow CO + H$ | (Dissociative) |
| $C^+ + e \rightarrow C + h\nu$ | (Radiative) |
| $Fe^+ + grain \rightarrow Fe + h\nu$ | (Grain) |

Organic Molecules;

Seeds of Life




Meissa
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M 78
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Alnilam
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Orion Nebula
Rigel
Saiph