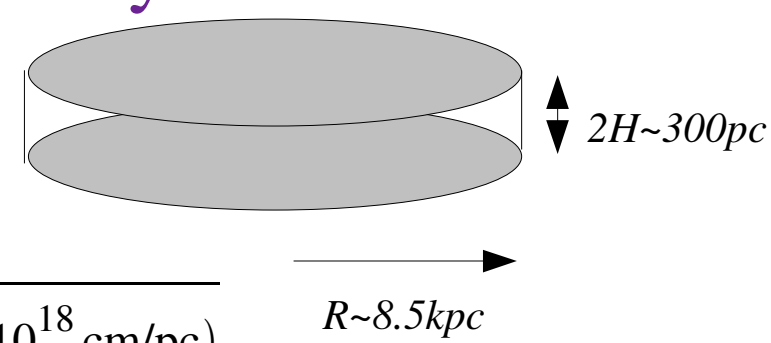
Overview of the Interstellar Medium

- Mass of stars in the Milky Way
  - 3-5x10^{10}Msun (Table 1.3 of Tielens wrong!)
- Mass of gas in the Milky Way
  - ~3x10^{9} Msun (inside solar circle) - 9x10^{9} Msun (<20kpc)
- Mean density of gas in the Milky Way

$$\bar{n}_H \approx \frac{M_{gas}}{(\pi R^2 2\mathrm{H})}$$

$$= \frac{5\times10^{9}\,\mathrm{Msun}\times2\times10^{33}\,\mathrm{g/Msun}}{1.67\times10^{-24}\,\mathrm{g/H}\times(8.5\,\mathrm{kpc}\times3\times10^{21}\,\mathrm{cm/kpc})^2(2\times150\,\mathrm{pc}\times3\times10^{18}\,\mathrm{cm/pc})}$$

$$= 0.3\,\mathrm{cm}^{-3}$$

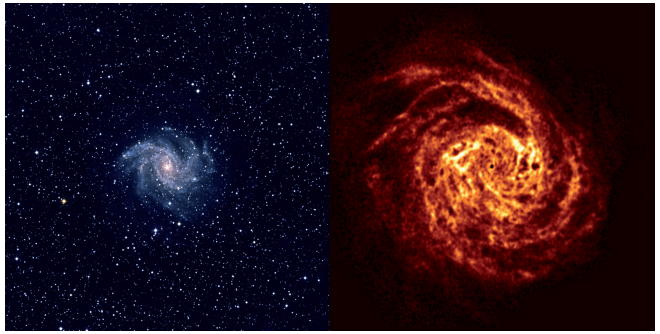


Density distribution

- About half the gas and half the volume in the Milky Way disk is in phases with density within a factor of two of n_H=0.3cm^{-3}.
- But most of the rest of the *volume* is in gas with density 100 times *lower*: n_H=0.003cm^{-3}.
- Most of the rest of the *mass* is in gas with 100-1000 times *higher* than the mean:n_H=30-300 cm^{-3}.

Differing spatial distributions

- Most of the dense (molecular) gas lies inside the solar radius (8.5 kpc).
- Most of the neutral atomic gas lies outside the solar radius.



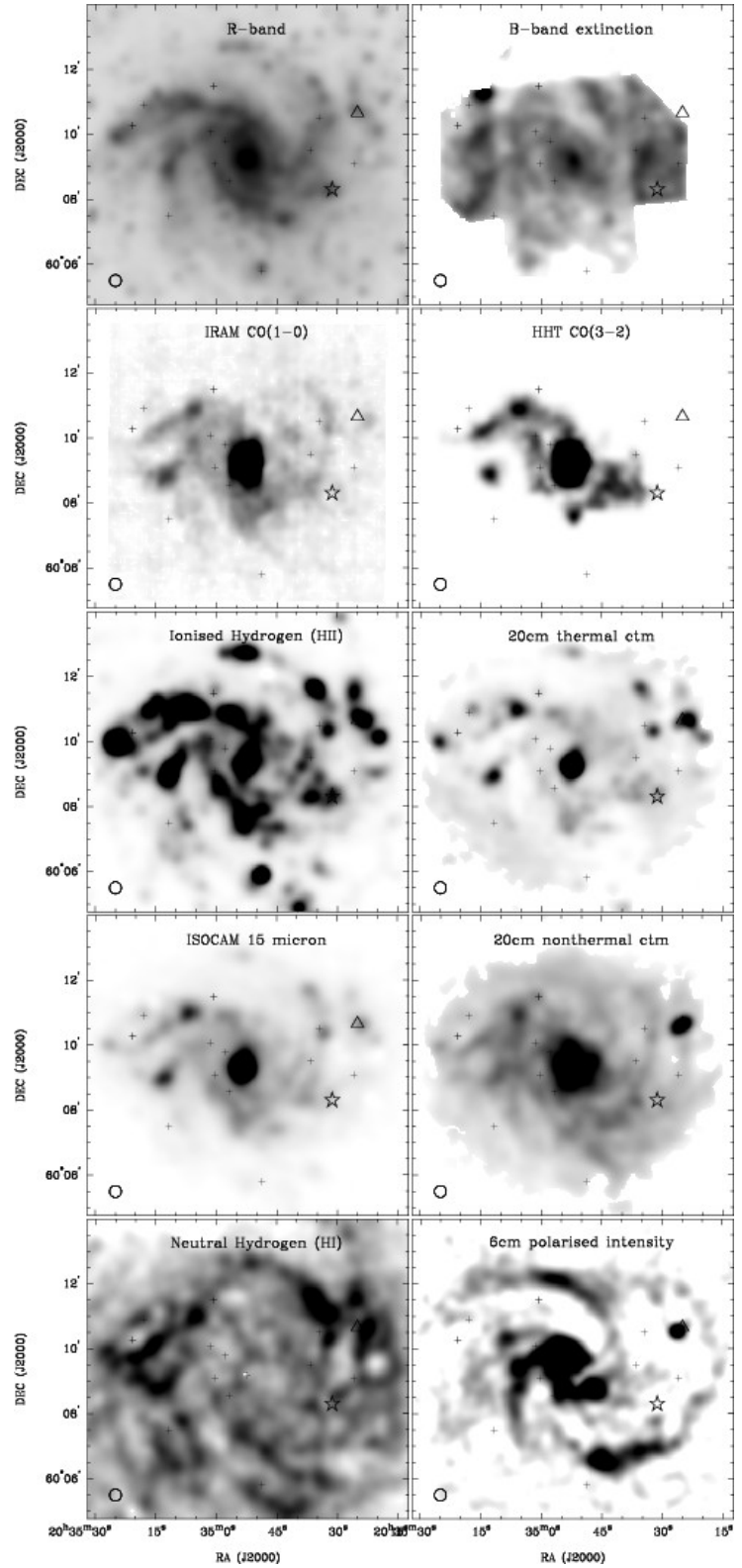
NGC6946 opt(L) 21cm(R)
Boomsma et al AA 490, 555

- The low density (hot) phase has a much larger scale height (~3kpc) than the neutral and molecular gas (~100pc).

Differing spatial distributions-2

NGC 6946
Walsh et al 2002
A&A 388, 7

As in Milky Way:
HI distrib much bigger
than everything else.
CO more centrally concentrated
than old stars (Rband) or
young stars (HII=Halpha image)



Uncertainty in Milky Way gas mass

somewhat model dependent (HI, CO seen everywhere, but need CO/H2 abundance, and HI distances are hard to deconvolve from the rotation curve. Other phases are not seen well except locally.

4.5×10^9 Msun (p19)

7.3×10^9 Msun (p 7)

Pressure equipartition

- Except for the densest gas and some dynamical regions, most of the interstellar medium is in rough pressure equilibrium, with $p_{tot} \approx 3 \times 10^{-12}\,\mathrm{dyn\ cm^{-2}}$
- Pressure supplied by roughly equal contributions from:
  - Thermal pressure $\sum_j n_j k T_j$
  - cosmic rays $\frac{1}{3}\sum_j \int_0^\infty f_j(p)\, p\, v\, d^3 p$
  - magnetic pressure $B^2/8\pi$
  - turbulent motions ρv^2

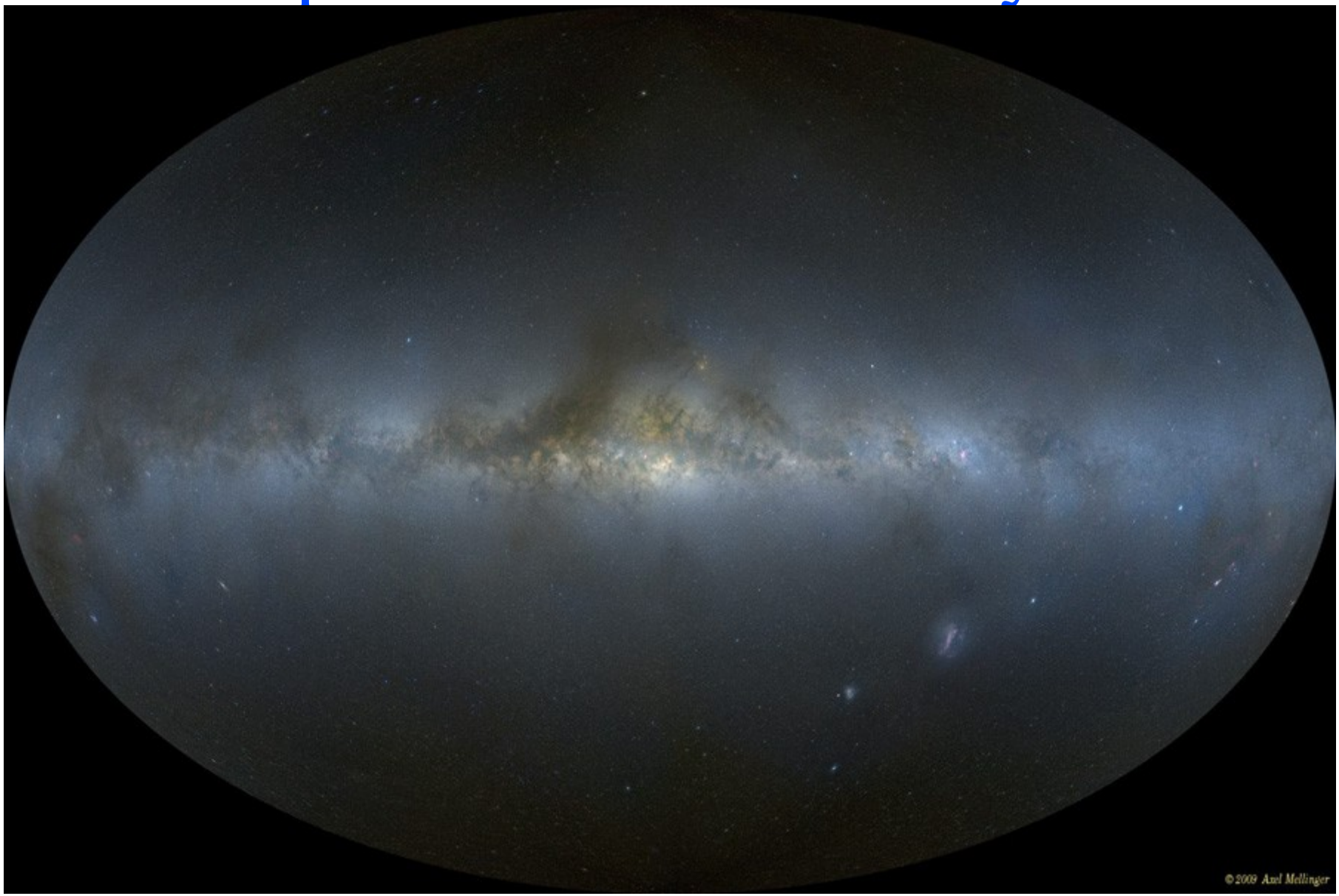
Identifying the components of the ISM

- The original "multi-messenger astronomy"
- Many equally important components of
  - Mass
  - Energy
  - Mass input, Mass sinks
  - Energy input (heating), energy output (cooling)
- No single wavelength of observation will reveal all (or even most of) the components!

Many messengers to deliver the ISM

- Only by combining radio, mm, IR, Opt, UV, X-ray, and gamma-ray imaging and spectroscopy and polarization measurements, plus particle (cosmic ray) detection over 50 years did we build up our current picture of the ISM.
- Omit any one of those, and we'd miss an important component.
  - Are we still missing an important ingredient!?

Optical view of the sky



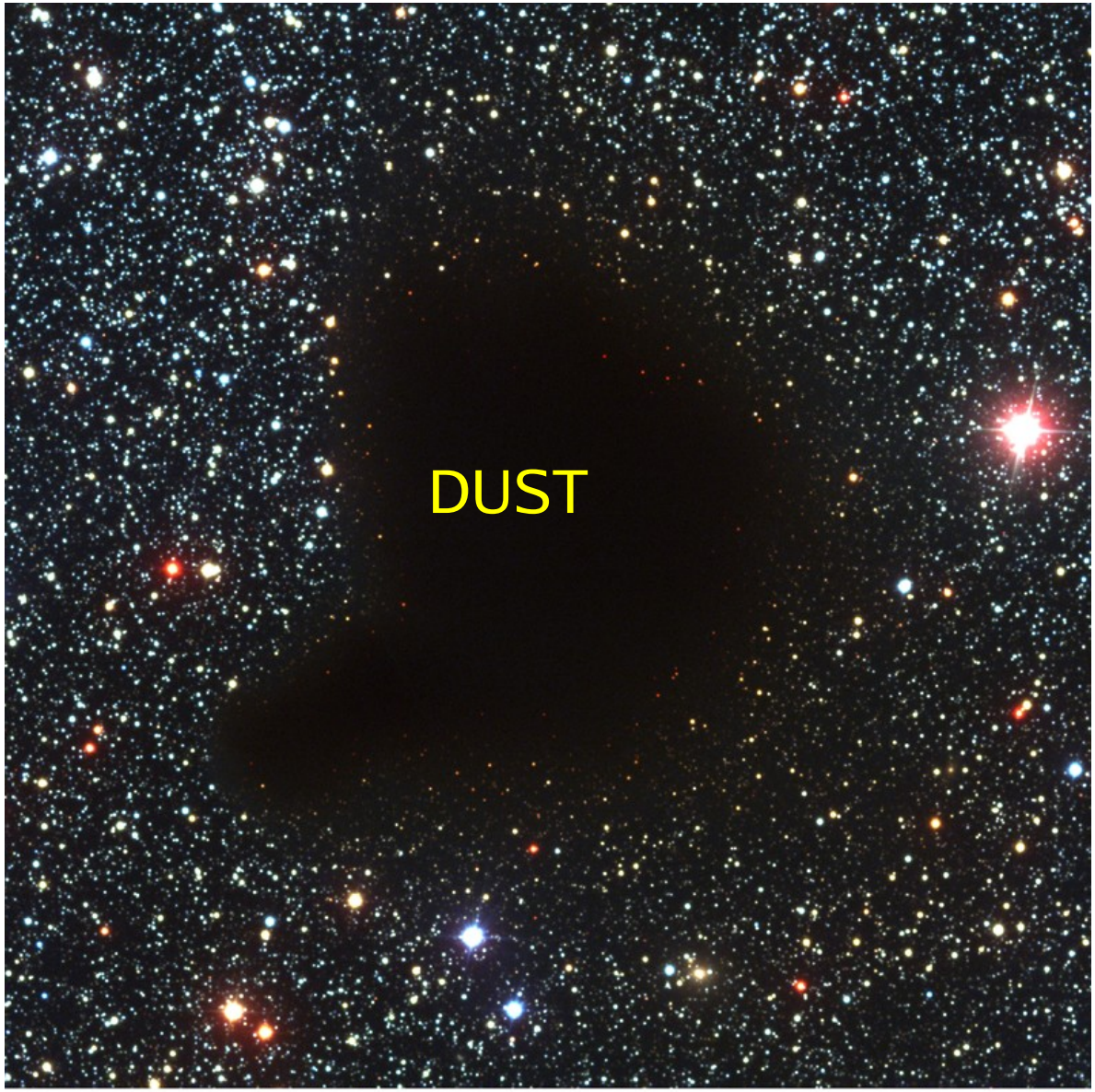
Mellinger PASP 121. 1180--1187 (2009)
http://home.arcor-online.de/axel.mellinger/

Optical: stars and ?

Notice stars shining through the edges of the dark cloud are redder than stars outside.

Compare dim, red sunset, especially after California fires or volcano eruptions.

Suggests scattering by particles smaller than wavclength of light: scatter blue light more than red.

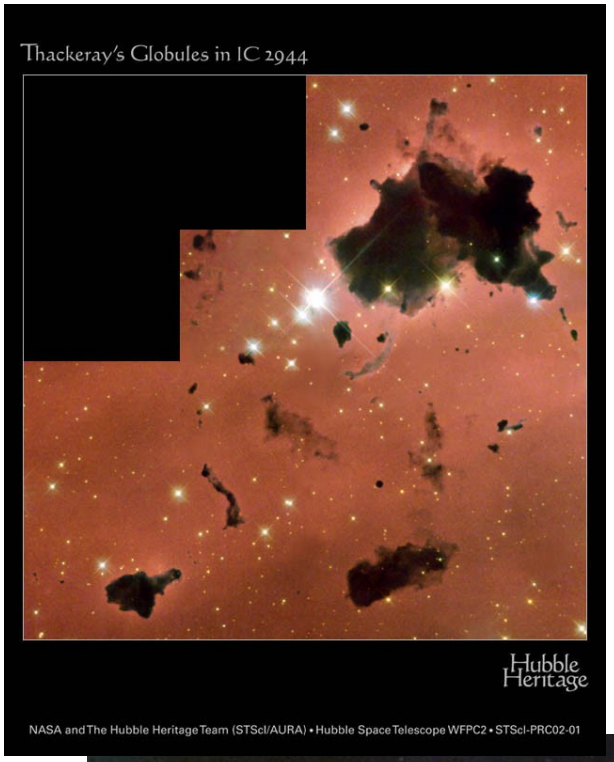


ESO PR Photo 20a/99 (30 April 1999)

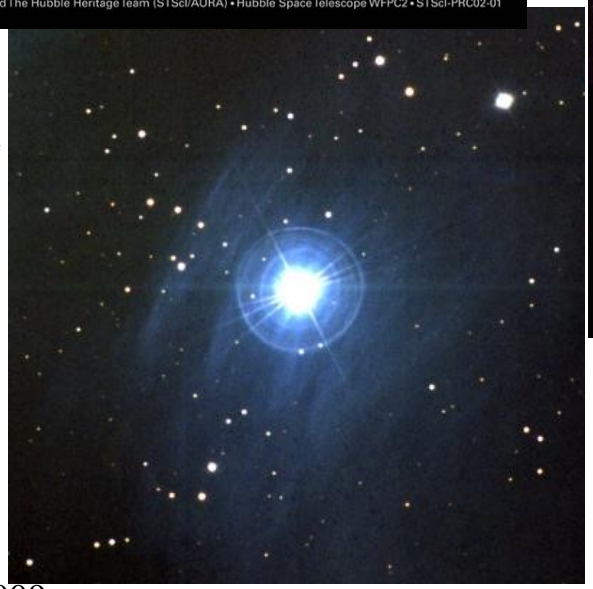
The "Black Cloud" B68
(VLT ANTU + FORS1)

Dust extinction vs reflection

See dust as black clouds when backlit: the dust absorbs and scatters the backlight away from our line of sight.



Reflection first demonstrated in spectrum of Merope nebula (R) by V.M. Slipher 1912, Lowell Obs Bull #55, Vol II, pp. 26-27



See dust as reflecting clouds when lit by a star in front of, or inside the dust (reflected light is usually slightly bluer than the star)

Dust reflection vs extinction

Left: dust extinction

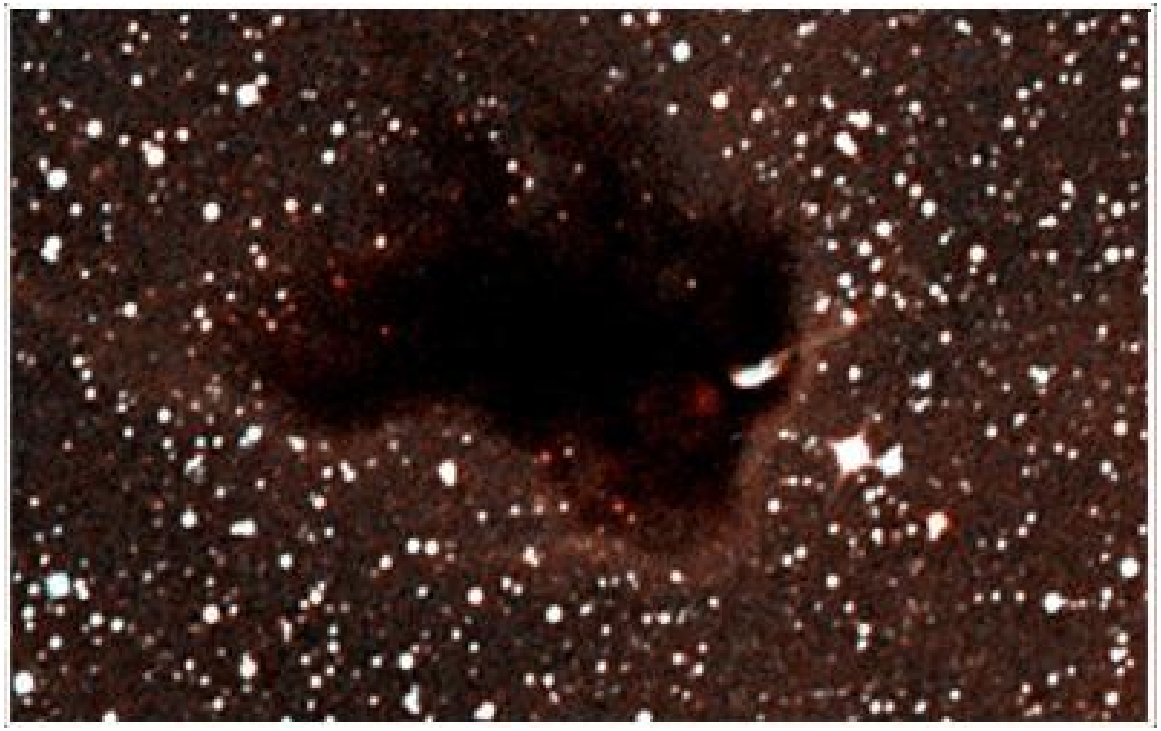
Right half: dust reflects light of Antares (very luminous red AGB star). Notice redder as move left, farther from Antares, as remaining transmitted light becomes redder.

Center: dust reflects light of a less bright hot blue star.

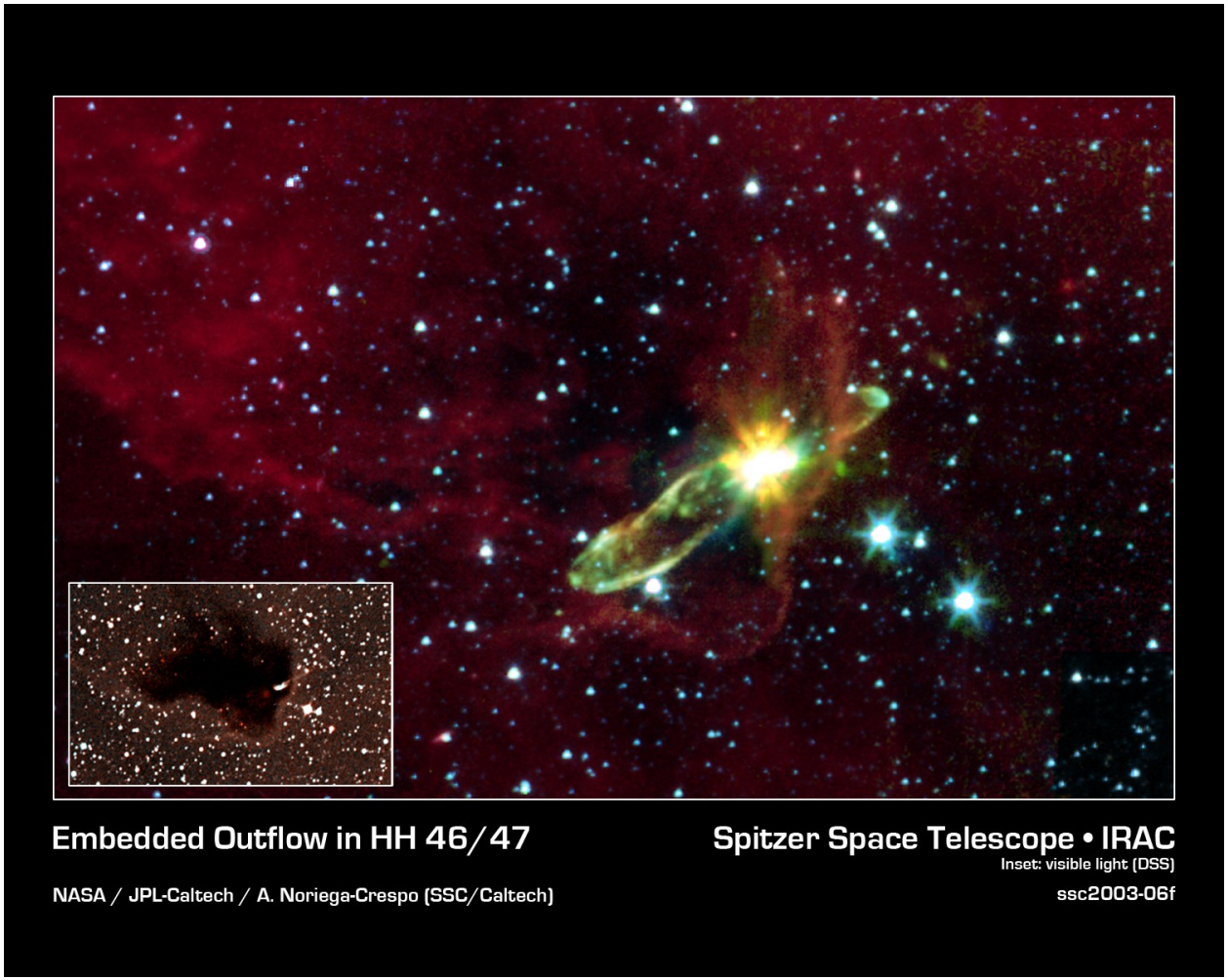
Antares/Rho Ophiucus Reflection Nebula

This region of the sky is within the Scorpius and Ophiucus constellations. Antares is a red supergiant star over 700 times the radius of our Sun in the Milky Way, and is often referred to as the 'heart of the scorpion'. The nearby nebula reflects its distinctive hue, leading to beautiful sunset colors. The small star cluster is the much more distant globular cluster NGC 6144. This region is a favorite among amateur astronomers, as it is one of the most colorful regions in the sky.

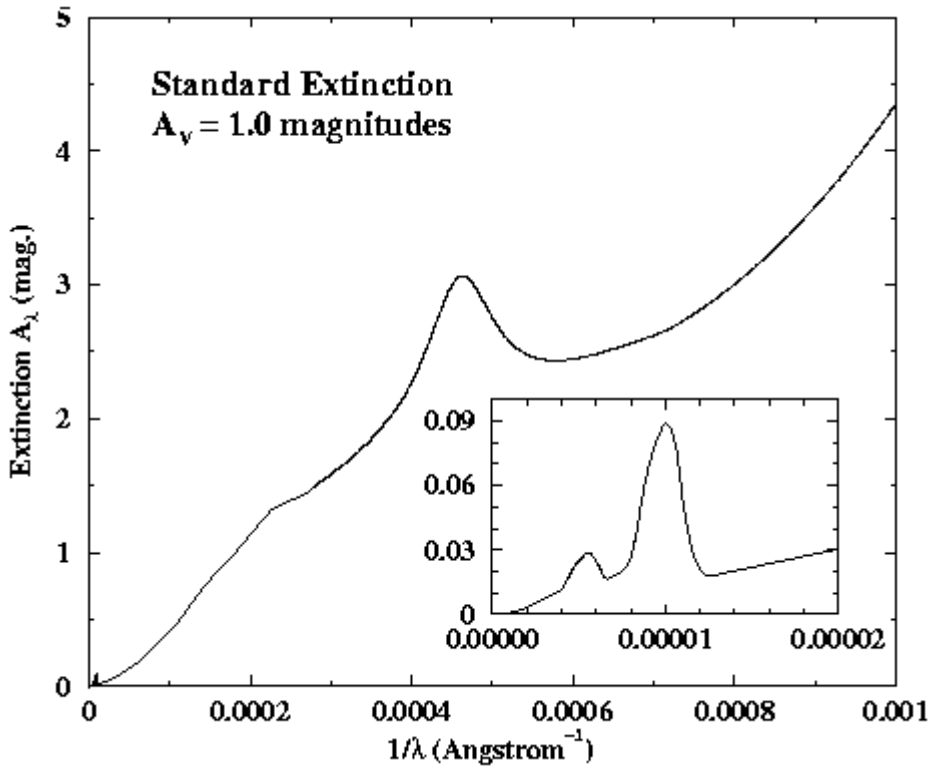
Optical: stars and dust



Infrared: more stars, less dust

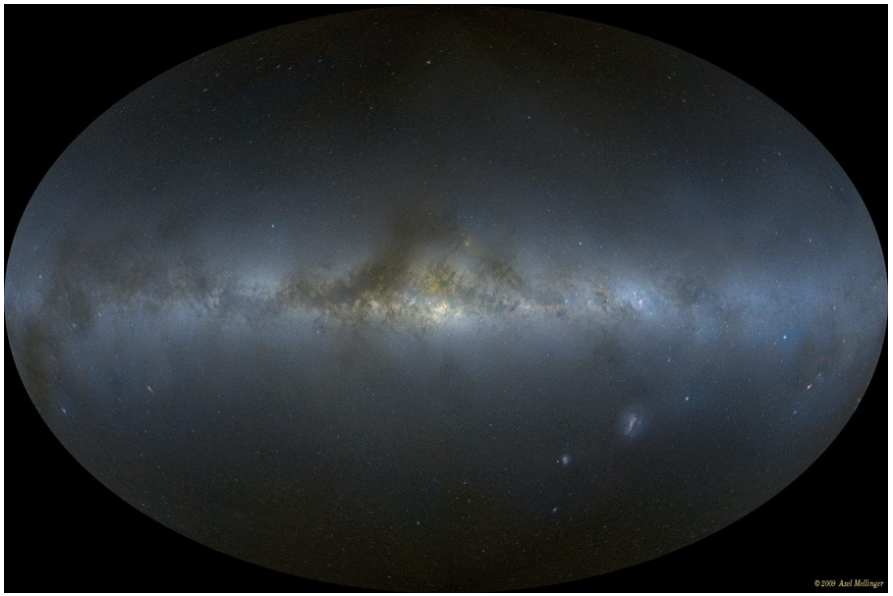


Dust extinction vs wavelength

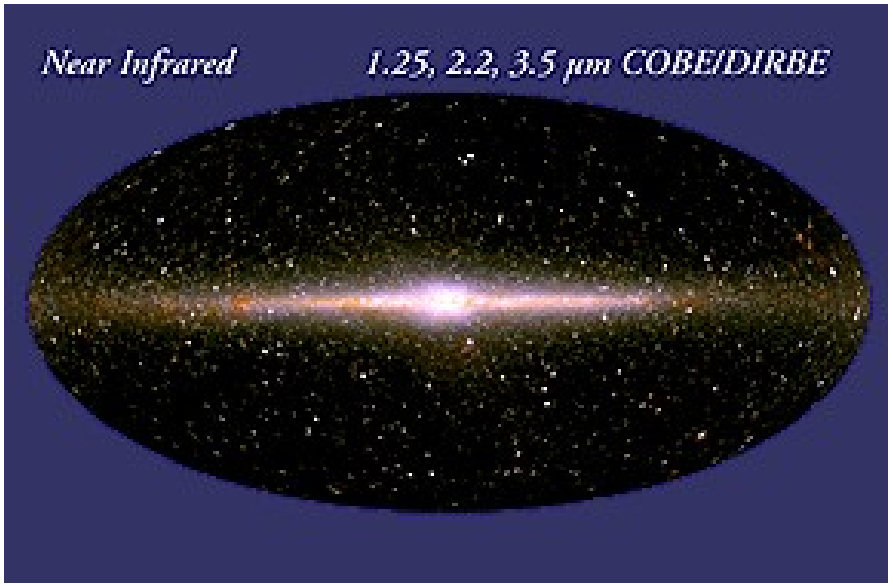


IR visible UV ->

Optical vs near infrared view of sky



Optical: stars, dust obscuration,
fat looking disk



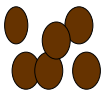
Near infrared: redder stars, much less
dust obscuration, much thinner looking disk,
clear bulge..

Dust extinction and the mean density

The smallest dust grains that scatter visible light effectively have

$$a \sim \frac{\lambda}{2\pi} \sim 0.1\,\mu\,\mathrm{m} \sim 10^{-5}\,\mathrm{cm}$$

Density of dust (graphite, silicate) is about $2\,\mathrm{g\ cm}^{-3}$



So optical depth 1 must have surface density of dust

$$\Sigma \sim 2\,\mathrm{g\ cm}^{-3} \times 10^{-5}\,\mathrm{cm} \sim 2 \times 10^{-5}\,\mathrm{g\ cm}^{-2}$$

With 1/4 of heavy elements condensed into dust

(i.e. 2 solar/4=0.01 of gas mass), this column density of dust

corresponds to a hydrogen column of $2 \times 10^{-3}\,\mathrm{g\ cm}^{-2}$, or

$$N_H = \frac{2 \times 10^{-3}\,\mathrm{g\ cm}^{-2}}{m_p} = 10^{21}\,\mathrm{cm}^{-2}$$

Dust extinction and the mean density

Optical depth 1 corresponds almost to 1 magnitude extinction, or in visual (550nm) light, $A_V = 1$.

Useful rough rule: $N_H \approx 10^{21} A_V$

Compare images of Milky Way in optical and near-infrared (where small grains don't scatter much, and there are fewer $a \sim \lambda$ grains).

In optical galaxy looks about 8 times thicker, since we don't see the distant stars making up the MW disk as we do in IR light.

Suggests we see only about 1/8 of the Galaxy in visible light, i.e. 1kpc

Thus mean density of dust-containing gas should be

$$\bar{n}_H \sim \frac{10^{21}\,\mathrm{cm}^{-2}}{1\,\mathrm{kpc}} = \frac{10^{21}\,\mathrm{cm}^{-2}}{3\times 10^{21}\,\mathrm{cm}} = 0.3\,\mathrm{cm}^{-3}$$

consistent with our first estimate (and much of the heavy elements being condensed in dust.

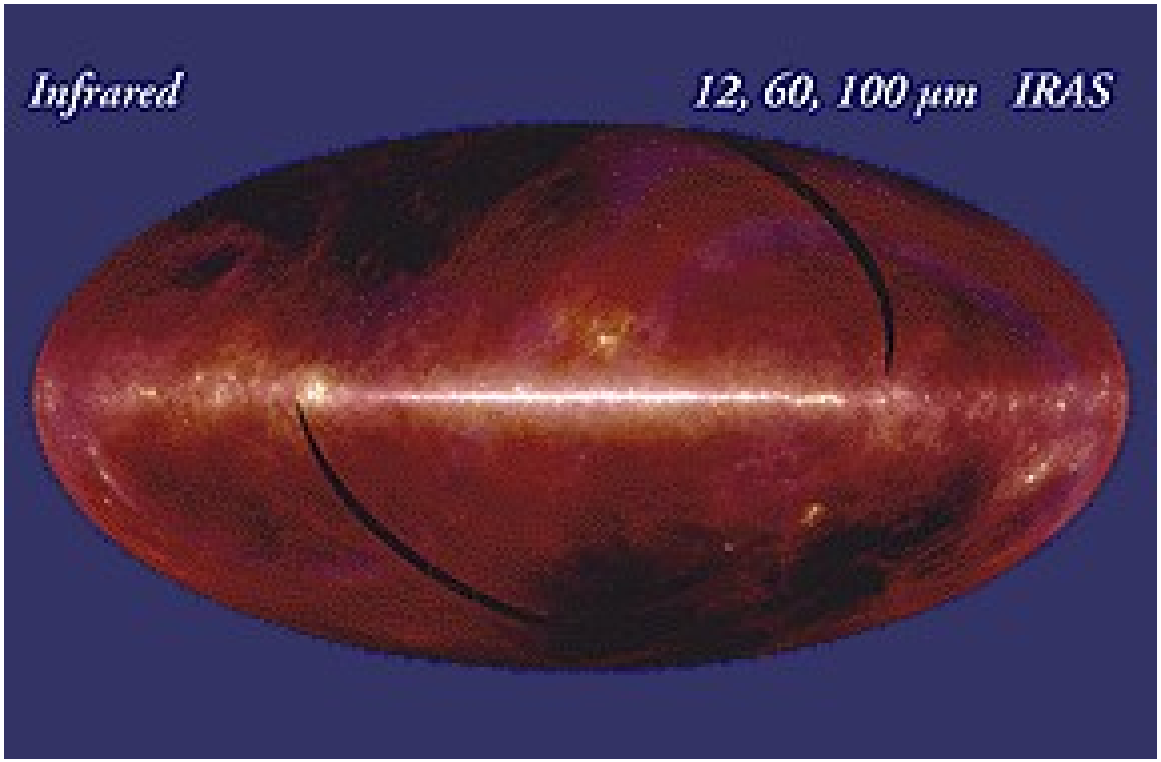
Dust thermal emission

The dust both scatters and *absorbs* light.

The absorbed light *heats* the dust.

The heated dust radiates like gray-body at equilibrium temperature T such that power absorbed = power radiated.

20-60K typical.

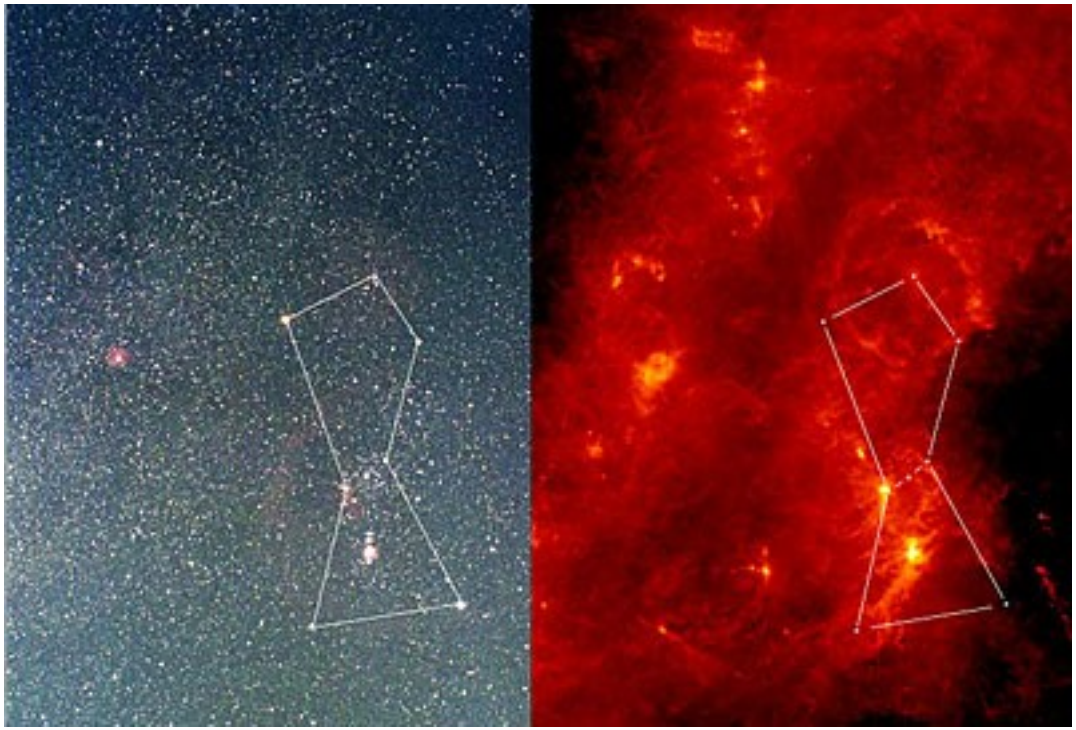


Wien displacement law:

$$\lambda_{max} = \frac{3000\,\mu\,\mathrm{m}}{T} = 150\,\mu\,\mathrm{m} - 50\,\mu\,\mathrm{m}$$

Dust absorbs ~ ½ the starlight of the Milky Way. So reradiated power ~ stellar luminosity/2.

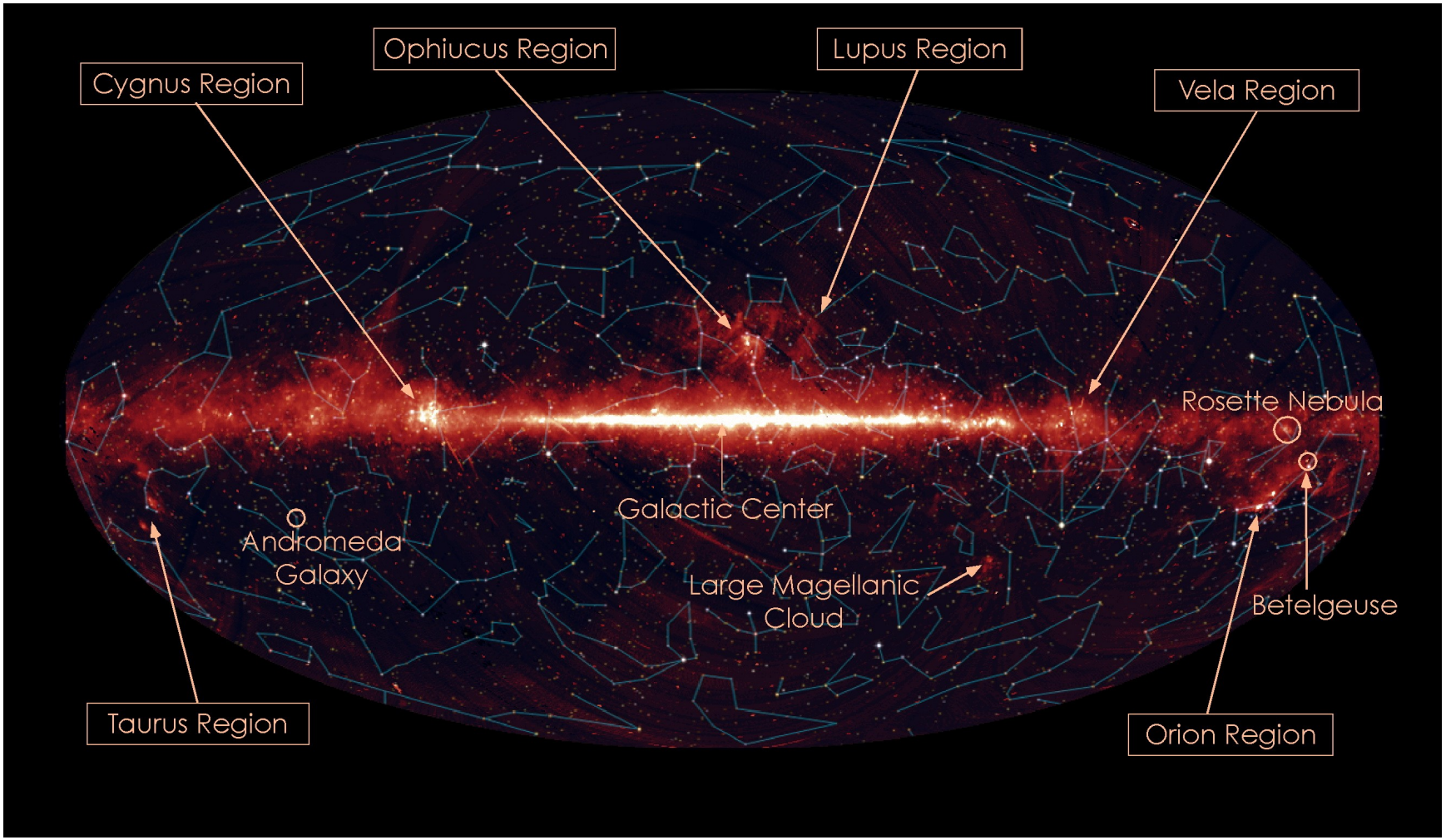
Dust thermal emission



Left: Optical image of Orion and Monoceros.

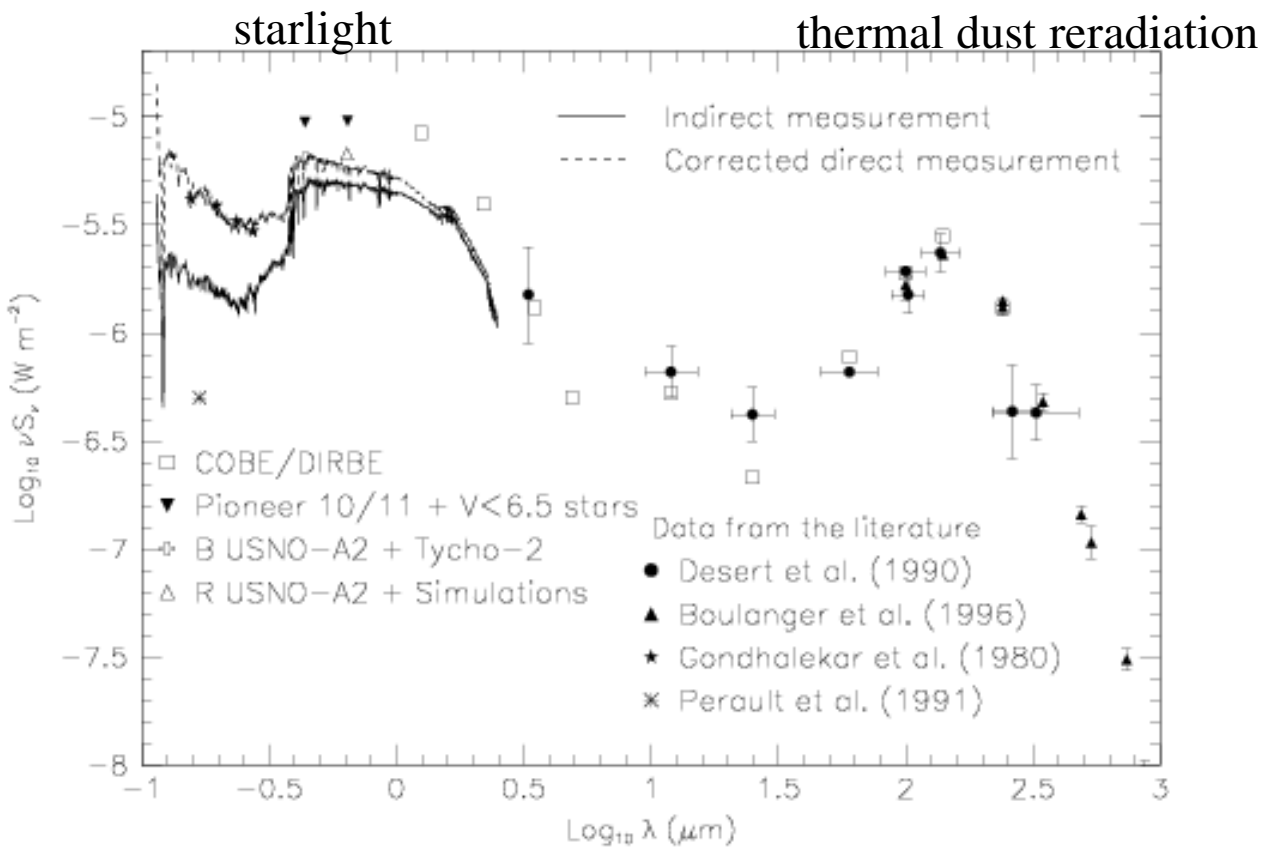
Right: 140 micron infrared image from *Akari* .Mission.

Hot dust (small grains)



Sky at 9 microns, from Akari spacecraft (2007). 9” resolution.

Surface brightness spectrum of solar neighborhood



Melchior, Combes & Gould 2007, A&A 642, 965

Properties of Dust

- Particle sizes 0.5nm-300nm
- size spectrum $dN/da \sim a^{-3.5}$
- extinction $A_\lambda \propto \lambda^{-1.7}$ IR-visible, $\propto \lambda^{-1}$ in visible
- dust albedo ~0.6 in visible; forward scattering.

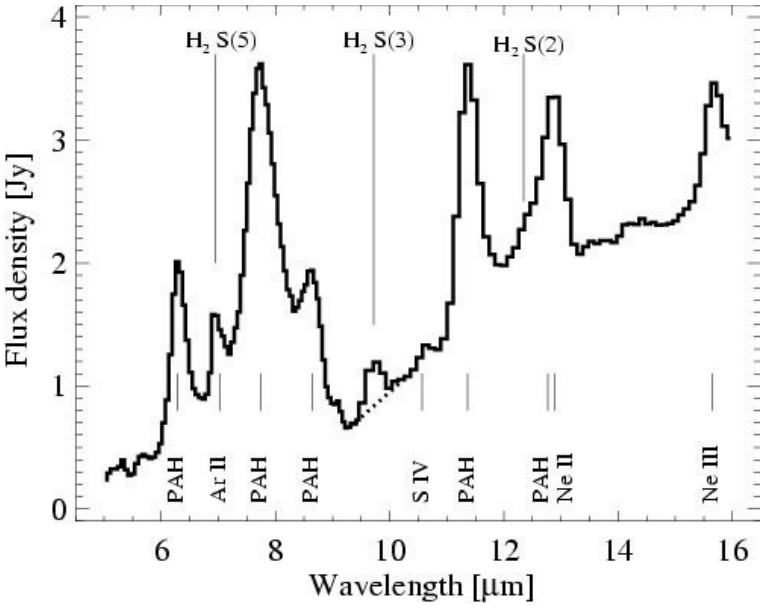
The smallest nano-dust

- finite specific heat
- single photon raises temperature a lot: temperature spikes
- PAH -vibrational bands
- smallest grains have largest

total contribution to UV

optical depth: large fraction

of luminosity!



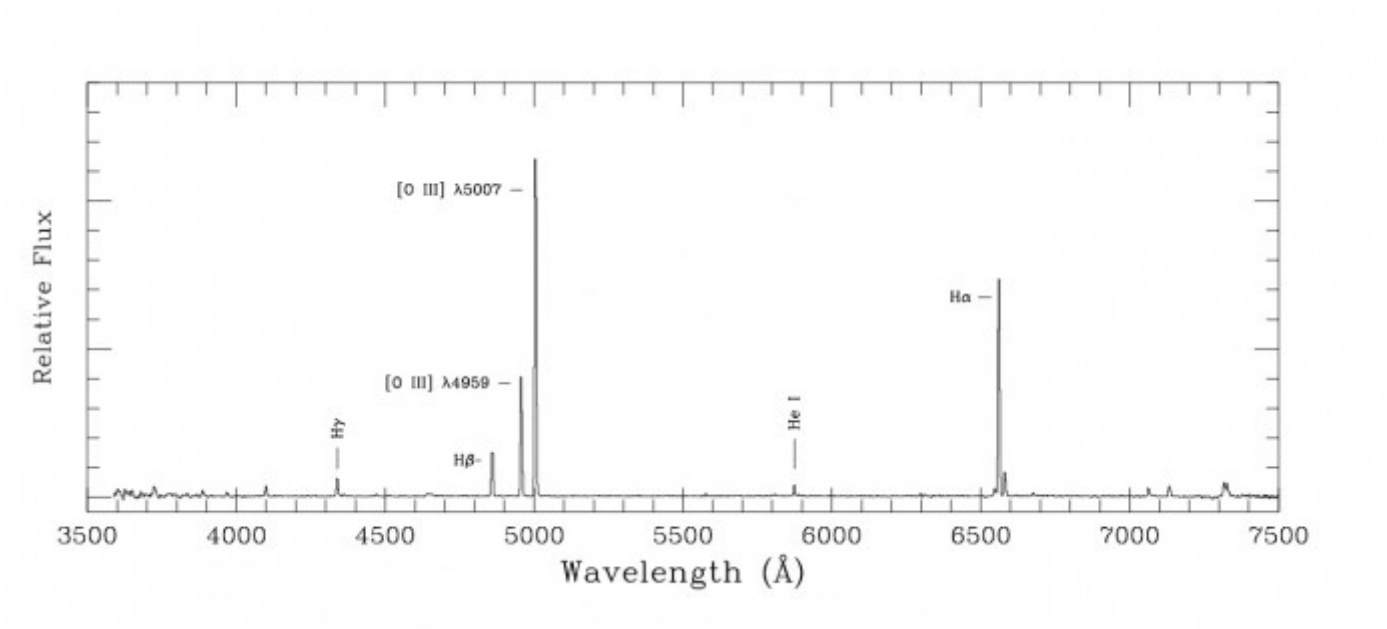
What else can we see in optical?

California nebula (mainly Halpha emission) and Pleiades (mainly dust reflection)

Ionized gas

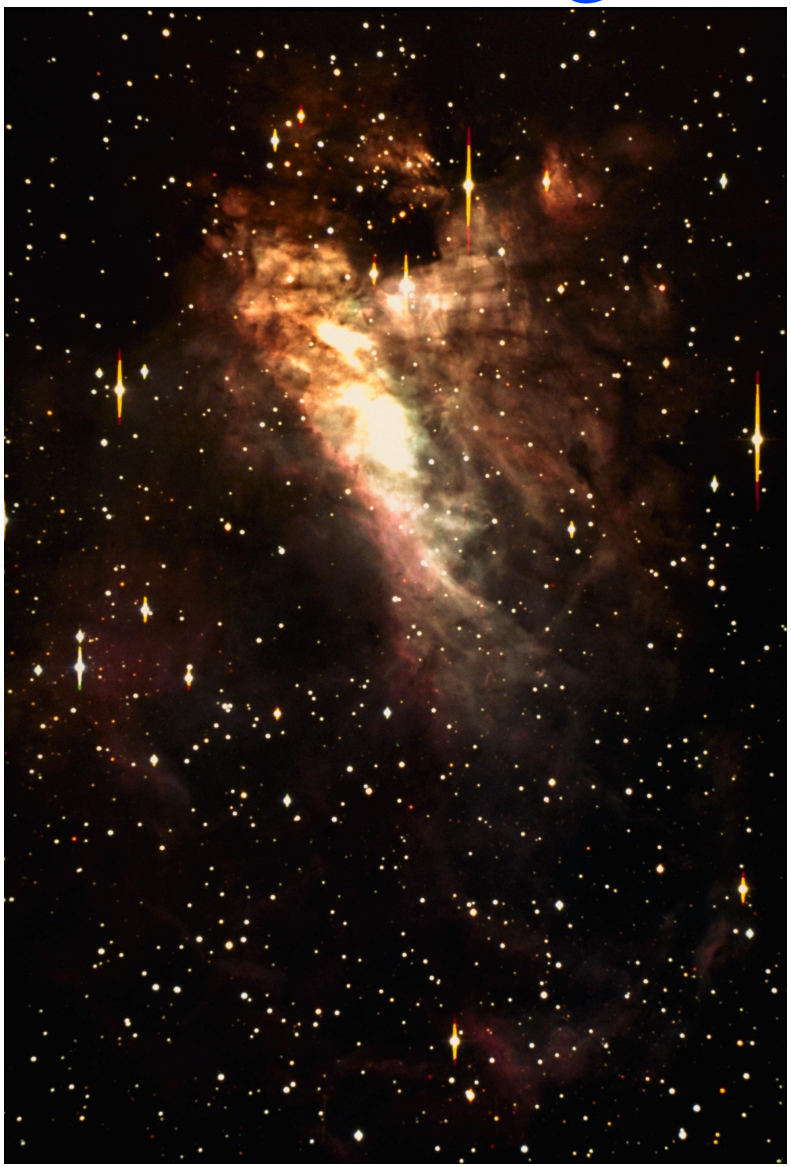
- UV photons from hot stars ionize surrounding gas. and heat it by ejection of photoelectrons.
- Gas recombines -roughly one Hα photon per photoionization=recombination.
- Cooling by fine structure lines (IR) and optical transitions between ground and low-lying levels of heavy elements.
- Emission vs reflection nebulae

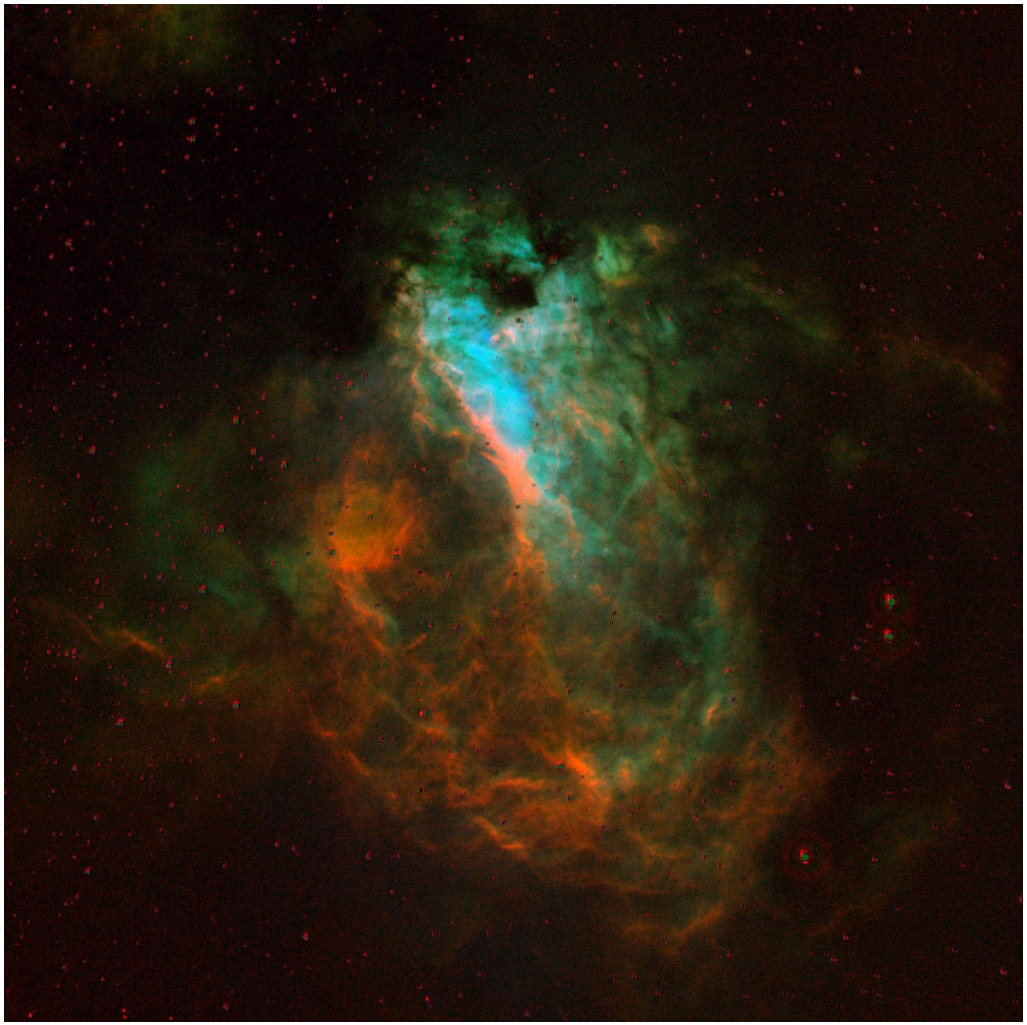
Ionized gas spectrum



Planetary nebulaspectrum from
https://www.e-education.psu.edu/astro801/content/l5_p2.html

Omega nebula: Messier 17





created from five frames imaged with filters covering a narrow range of wavelengths centered on the emission lines of SII (6731 angstroms), HeI (6678), H-alpha (6563), OIII (5007), and H-beta (4861). The red, green and blue contributions to the final picture come from, respectively, the ratios H-alpha/SII, SII/HeI, and OIII/H-beta.

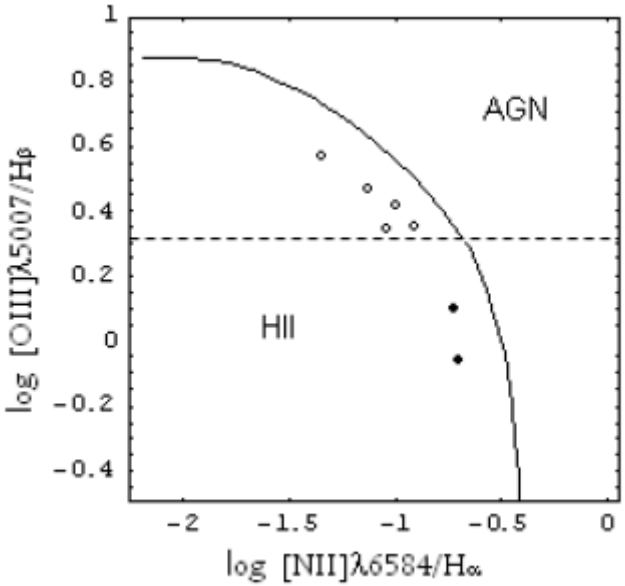
"True" color, gas about 800 Msun,,
5 pc across, 35 stars.

http://www.noao.edu/image_gallery/html/im0802.html

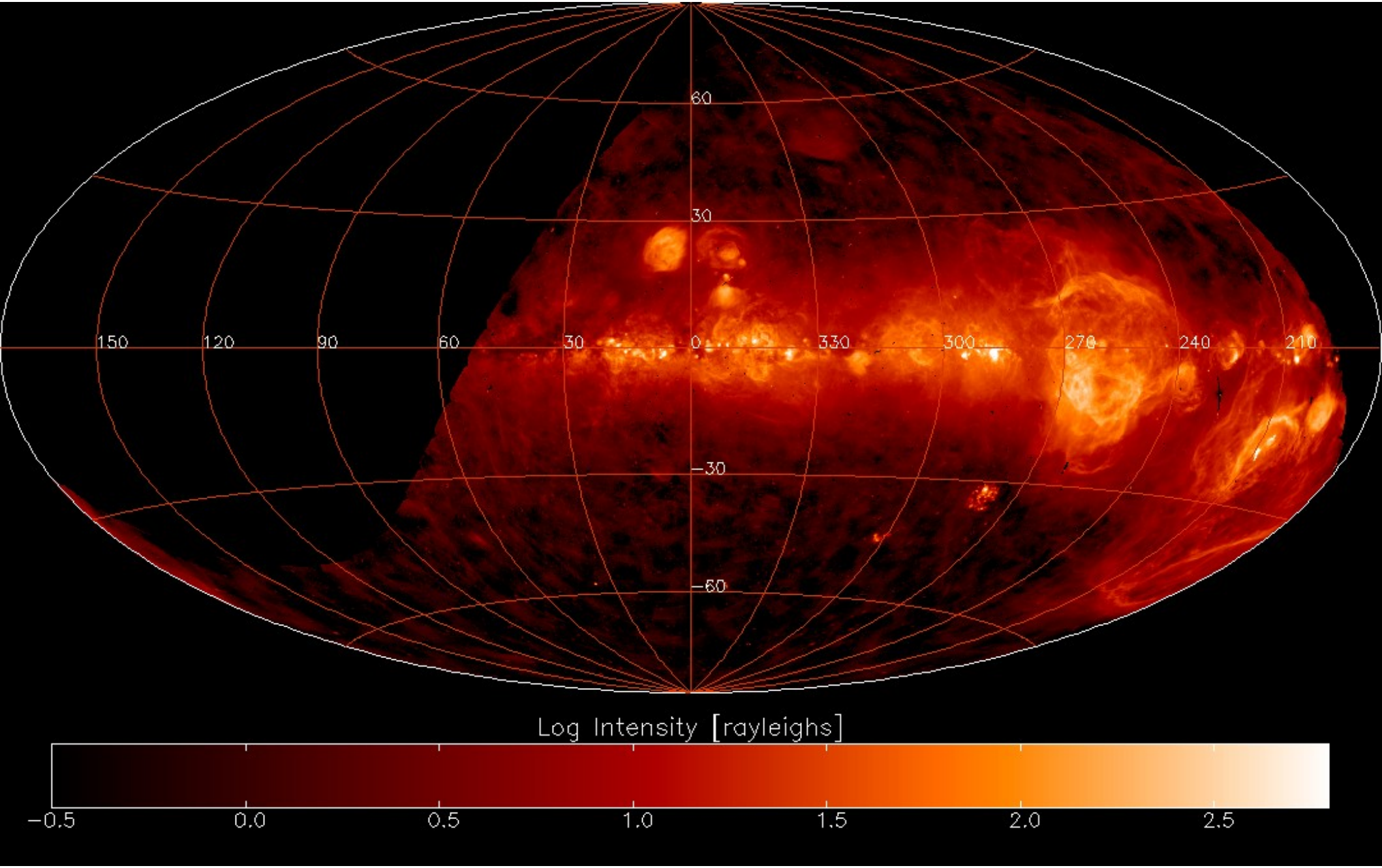
E.S. Phinney, Ay 126, Jan 5 2009

Emission lines as diagnostic tools

- [OIII]λ4383/[OIII]λ5007 diagnoses T_e
- Other line intensity ratios, e.g.[SII]λ6717/[SII]λ6731 diagnose n_e density
- Still others
  - ionization parameter,
  - shape of ionizing spectrum, etc



Ionized gas – Hα emission



E.S. Phinney, Ay 126, Jan 5 2009

1 Rayleigh=10^6/(4 Pi) photons/cm^2/s/sr

In emission, you see what is dense, not what is important (in mass).

Hα emission surface brightness is given by an integral along the line of sight $S_\alpha \propto \int n_e n_i dl = \int n_e^2 dl$

since $n_e = n_i$ for hydrogen.

So it is dominated by dense regions. Example:

1. Cloud $n_e = 30\,\mathrm{cm}^{-3}, l = 1\,\mathrm{pc} \rightarrow S_\alpha = 10^3\,\mathrm{cm}^{-6}\,\mathrm{pc}$

2. Diffuse medium $n_e = 0.1\,\mathrm{cm}^{-3}, l = 1\,\mathrm{kpc} \rightarrow S_\alpha = 100\,\mathrm{cm}^{-6}\,\mathrm{pc}$

Most of galactic Hα luminosity is from small dense clouds. Most of the mass is in diffuse gas. Roughly one Hα photon per ionizing photon absorbed.

Ionized gas -pulsar dispersion measures

A measure of the ionized gas density, rather than density^2 comes from the dispersion of radio pulses in the ISM.

In plasma, photons EM field interacts with free electrons.

Dispersion relation

$$\omega^2 = c^2 k^2 + \omega_p^2 \text{ where}$$

$$\omega_p^2 = 4\pi n_e e^2 / m_p$$

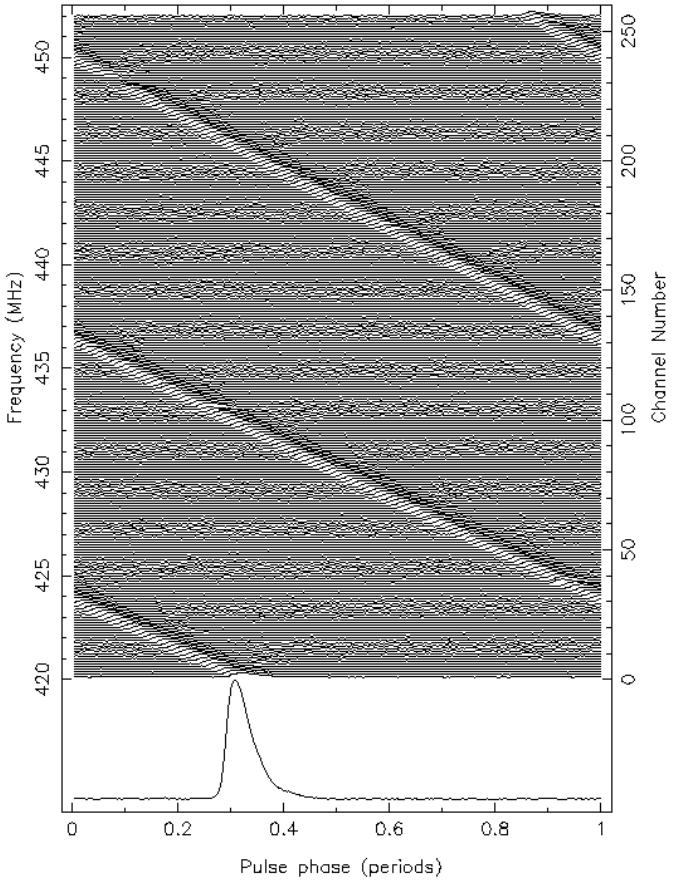
Group velocity $d\omega / dk = c(1 - \omega_p^2/\omega^2)^{1/2} \approx c(1 - \omega_p^2 / 2\omega^2)$

Pulse delay between frequencies $\nu_1 \wedge \nu_2$

$$\Delta t = 4.1\,\text{ms}\, DM\,[(\nu_2/\text{GHz})^{-2} - (\nu_1/\text{GHz})^{-2}]$$

where $DM\,(\text{cm}^{-3}\,\text{pc}) = \int n_e\, dl$ is integrated electron density along the line of sight to the pulsar.

In galactic plane, find $\langle n_e \rangle \approx 0.03\,\text{cm}^{-3}$



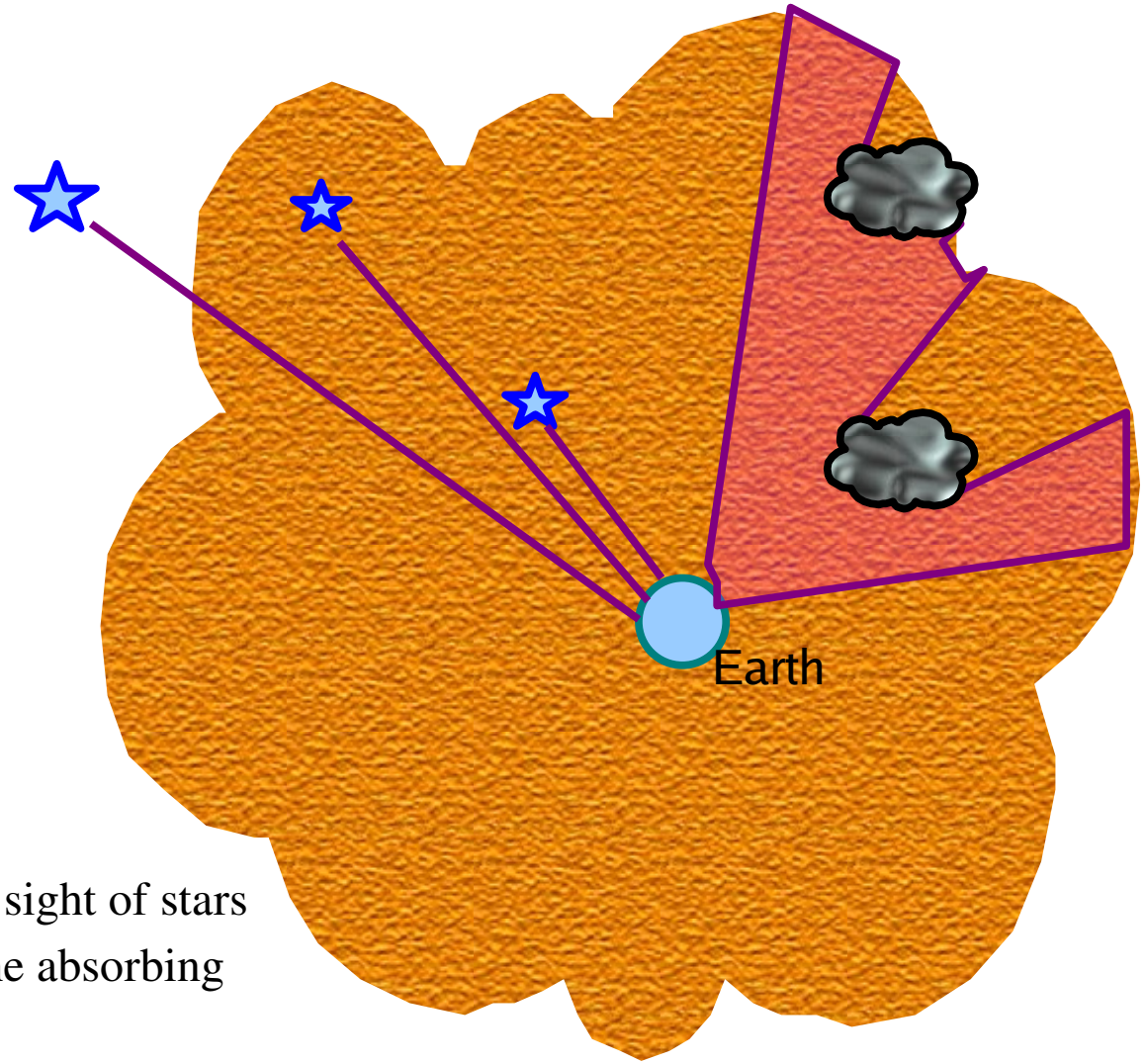
Pulses from the Vela pulsar arrival time versus frequency.

How to probe the hot gas of the ISM

ionization potentials

OI	13.6eV	CI	11.3eV
OII	35.1eV	CII	24.4eV
OIII	54.9eV	CIII	47.9eV
OIV	77.4eV	CIV	64.5eV
OV	113.9eV	CV	392eV
OVI	138.1eV	CVI	490eV
OVII	739.32eV(!)		
OVIII	871.39eV		

$113.9\text{eV}/k = 1.3\times10^6\text{K}$



Absorption lines due to gas along the line of sight of stars at various distances D. Gives for each ion the absorbing column densitys N_i as a function of distance.

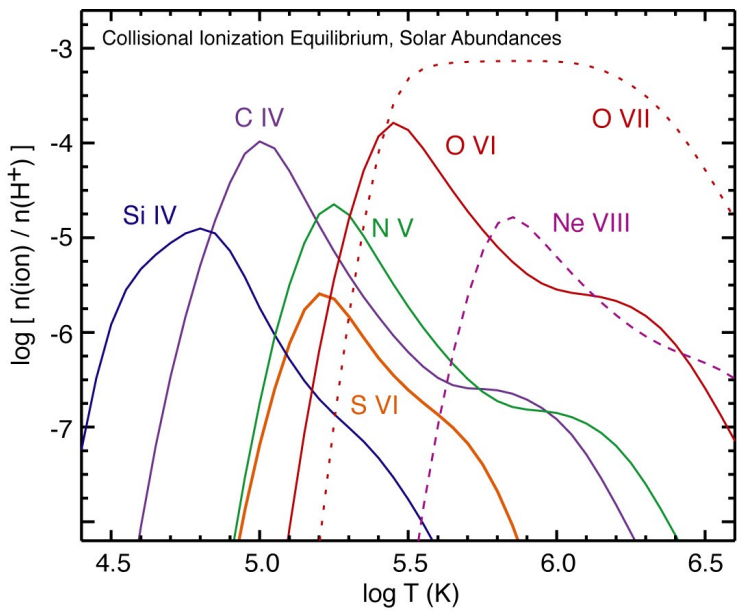
The ratios of lines in different ionization states of an element determine temperature T of gas, and fraction $f_i(T)$ of gas in each ionization state i. Hence can determine both T and $\langle n_H \rangle = N_i/(f_i D)$

Dense cold clouds shadow the X-ray emission from the hot gas, determine $\int_0^D n_i n_e \, dl$

Historical note

- Dark Clouds in Milky Way pointed out by William Herschel, 1785. He thought they were “Holes in the Heavens”.
- E.E. Barnard's spectacular photographs convinced him that dark clouds were not holes, but “really obscuring bodies” (1919). Wolf (1923) and Bok (1931) quantified their extinction by star counts.
- Wilhelm Struve (1847) pointed out general interstellar extinction, and Jacobus Kapteyn (1909) quantified to 1.6 mag/kpc. Kapteyn, and more quantitatively Robert J. Trumpler (1930) demonstrated λ^{-1} reddening (selective extinction).
- absorption lines due to interstellar gas along the line of sight to stars discovered and correctly explained by Vesto Slipher 1909, Lowell Observatory Bull, 51, Vol II, pp 1-2.

Hot Gas



Fractional abundance relative to Hydrogen of ions as a function of temperature in collisional ionization equilibrium.
From B.D. Savage, using Sutherland & Dopita 1993 CIE, Anders & Grevesse 1989 abundances.

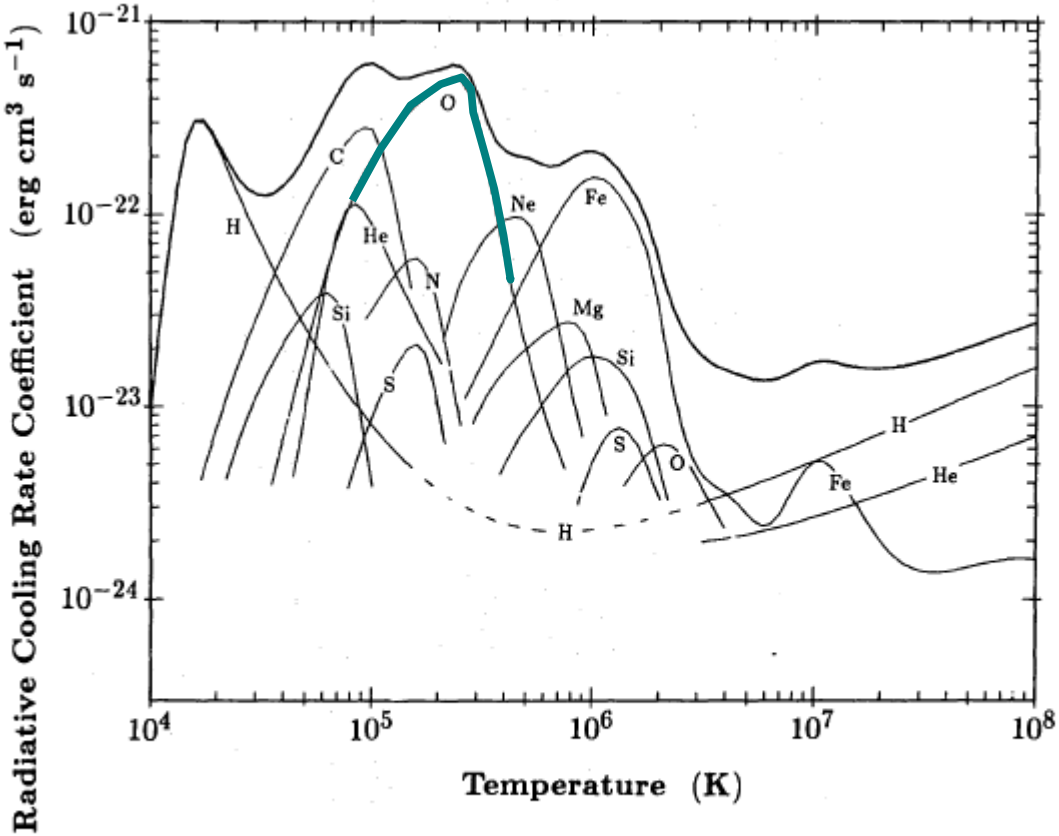
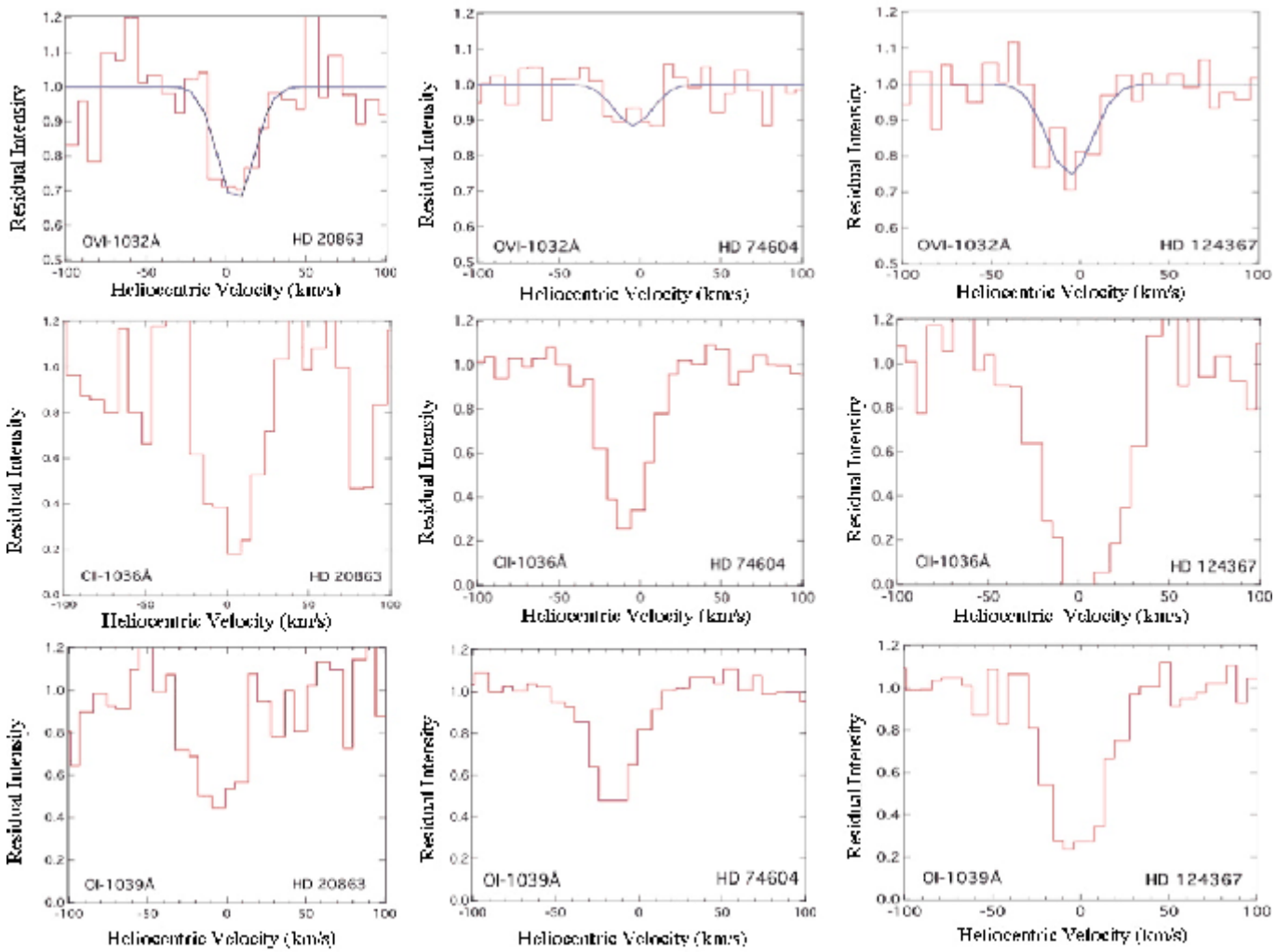


Fig. 2. Contribution of the different elements to the total radiative cooling coefficient for solar abundance of the elements

Notice that around 3×10^5 K, where OVI dominates the cooling, $d\Lambda/dT<0$: if you heat it, it cools less, if you cool it, it cools faster -i.e. it is thermally unstable, so no equilibrium at this temperature (prefers $>3\times10^6$K or $<10^5$K).

Hot gas -UV lines of OVI



Welsh & Lallement 2008 A&A, 490, 707

ionization potentials

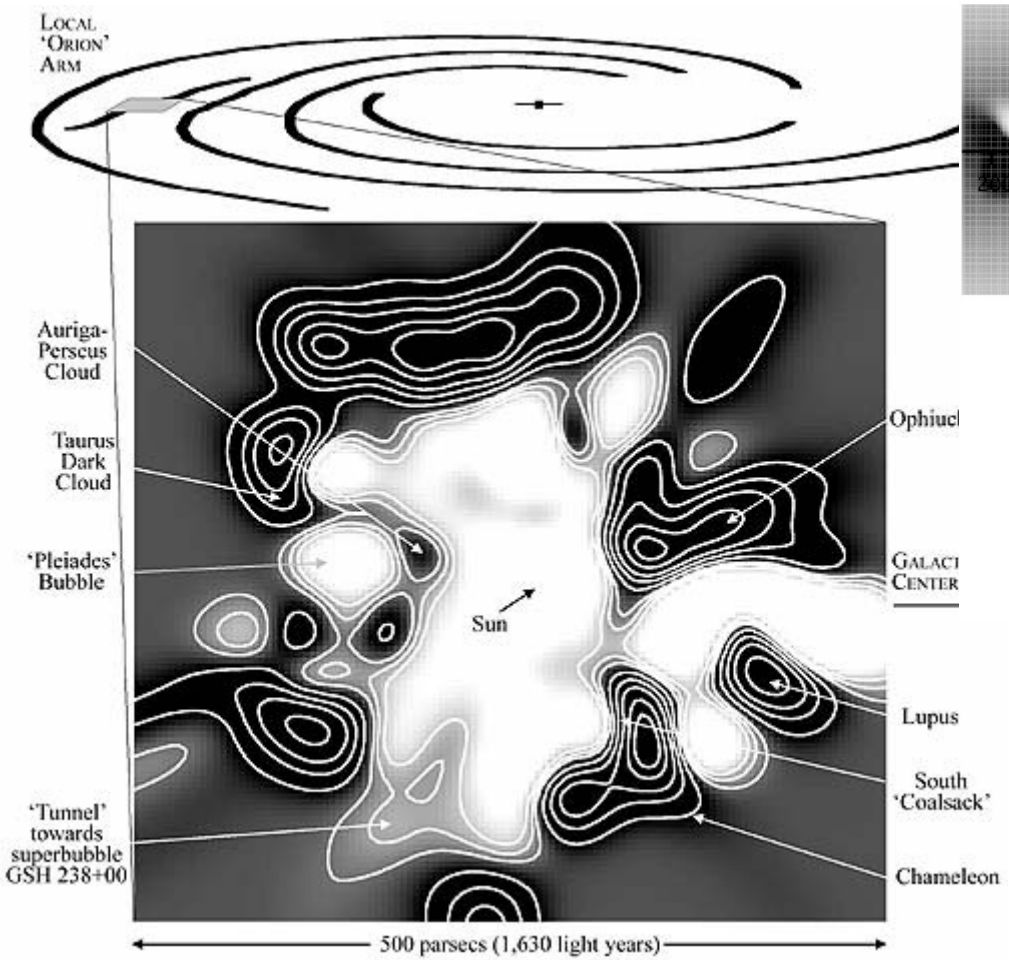
OI	13.6eV
OII	35.1eV
OIII	54.9eV
OIV	77.4eV
OV	113.9eV
OVI	138.1eV
OVII	739.32eV(!)
OVIII	871.39eV

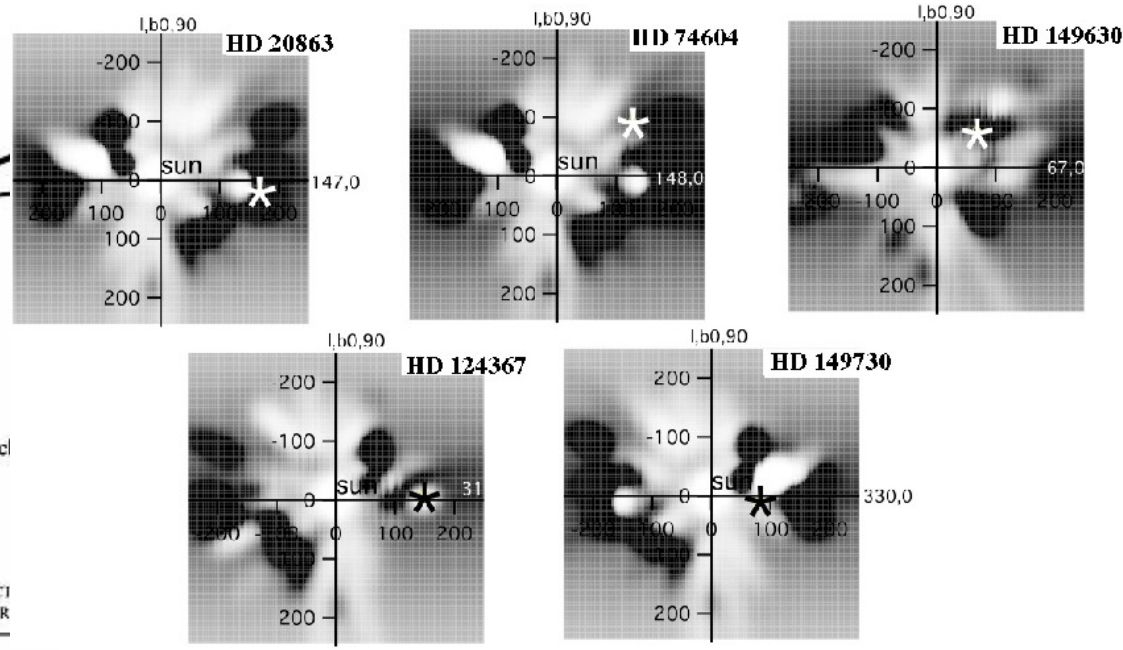
$113.9\text{eV}/k = 1.3\times10^{6}\text{K}$

OVI and CIV are both lithium-like. The transition (1032A in OVI, 1548A in CIV, 6707A in LiI) is the transition between outer e- in 2p to the (ground) 2s.

It is a $^2P^0$ to ^2S transition.

Hot gas -results of OVI UV studies





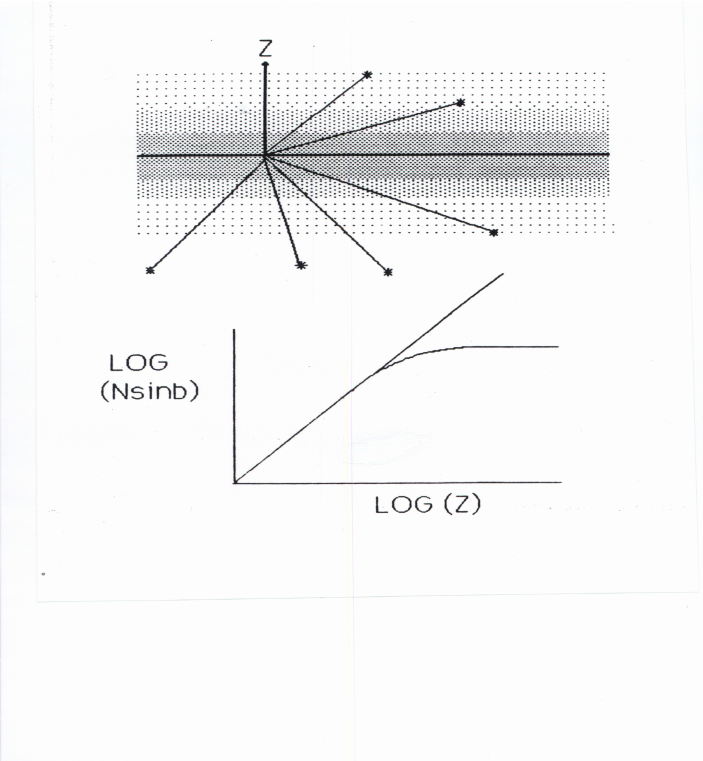
Locations relative to the local bubble and surrounding neutral gas clouds of the 5 B stars in which OVI absorption was detected.

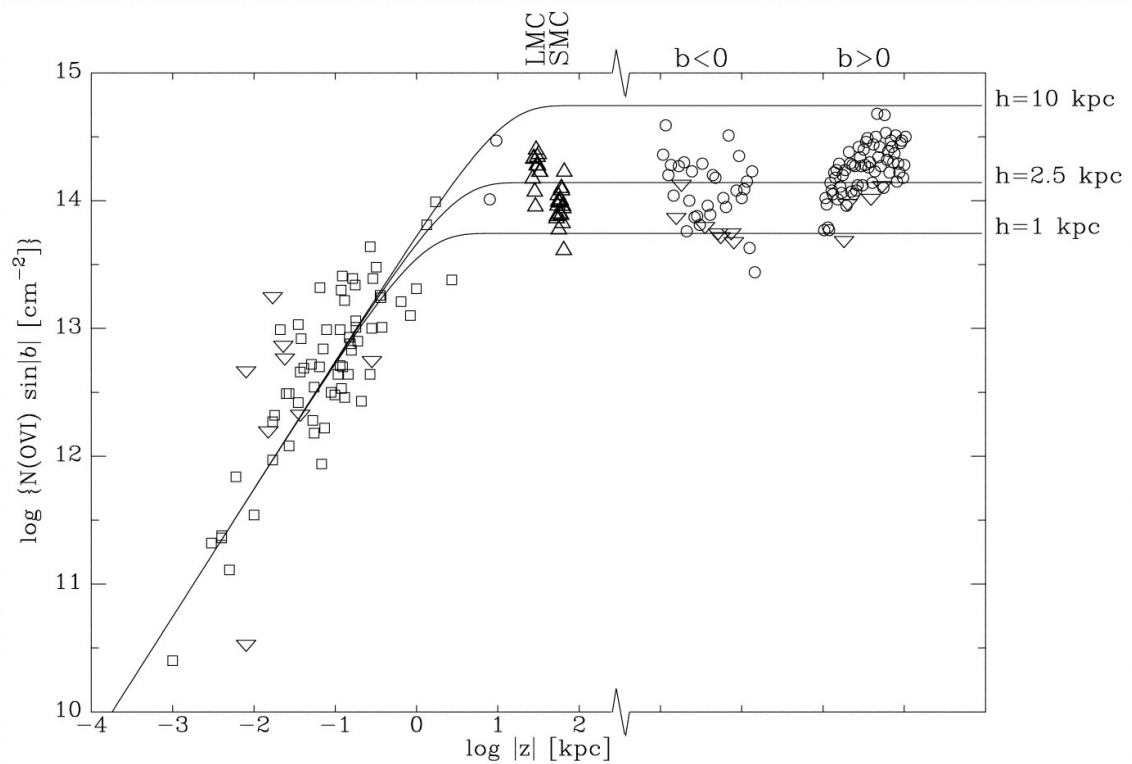
Welsh & Lallement 2008 A&A, 490, 707

Sun is in a bubble or "chimney" of hot gas

Note: the high columns of OVI are thought to come mainly from 300,000K gas produced at transition layers between neutral clouds and 10^6 K bubble gas, not the bubble gas itself.

Scale height of hot gas from UV absorption lines



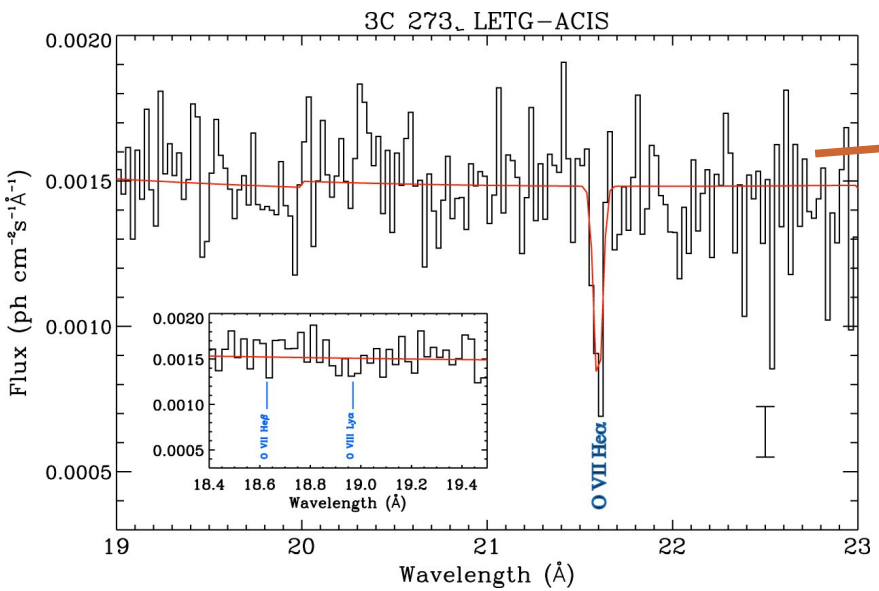


B. Savage 2005

EXPONENTIAL SCALE HEIGHTS (HST +FUSE)

Si IV	**5.1±0.7 kpc**
C IV	**4.4±0.6 kpc**
N V	**3.3±0.5 kpc**
O VI	**2 to 4 kpc**

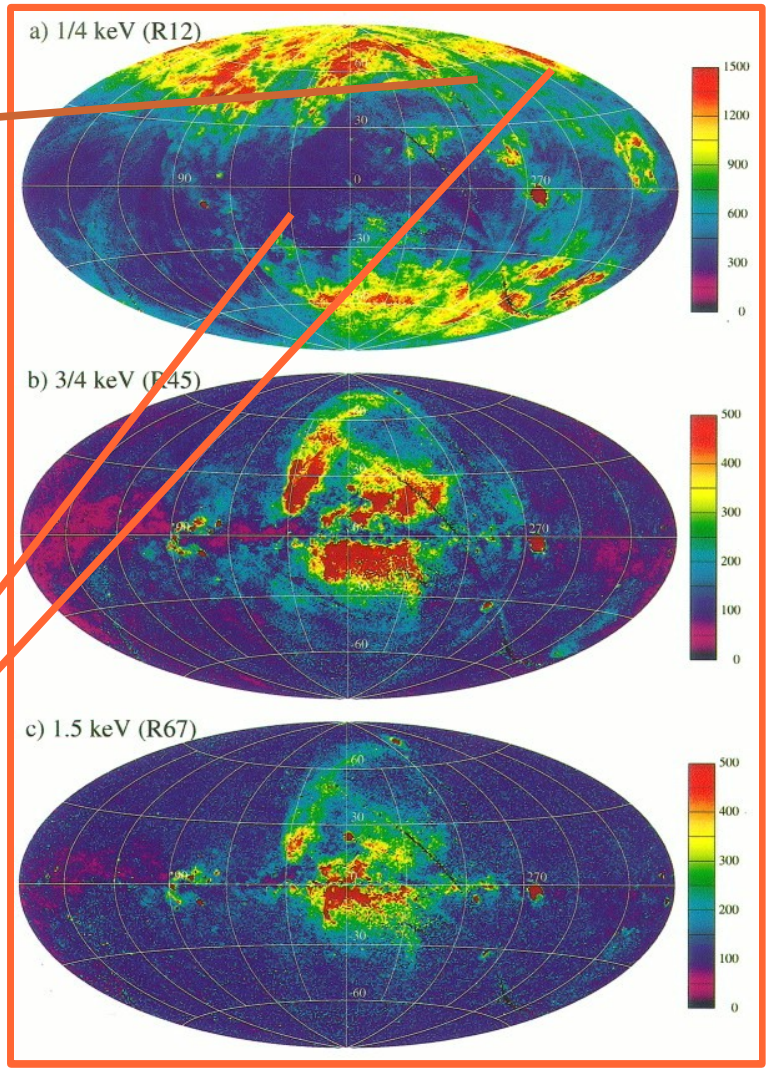
Hot Gas X-ray Kα, Kβ lines



3C273

4U1957+11

Mrk 421



Chandra detection of OVII Heα line in absorption towards the quasar 3C273

Fang et al 2003 ApJ 586, L49.

More recent Chandra results on QSO z=0 abs:

Yao et al 2008 ApJ 672, L21

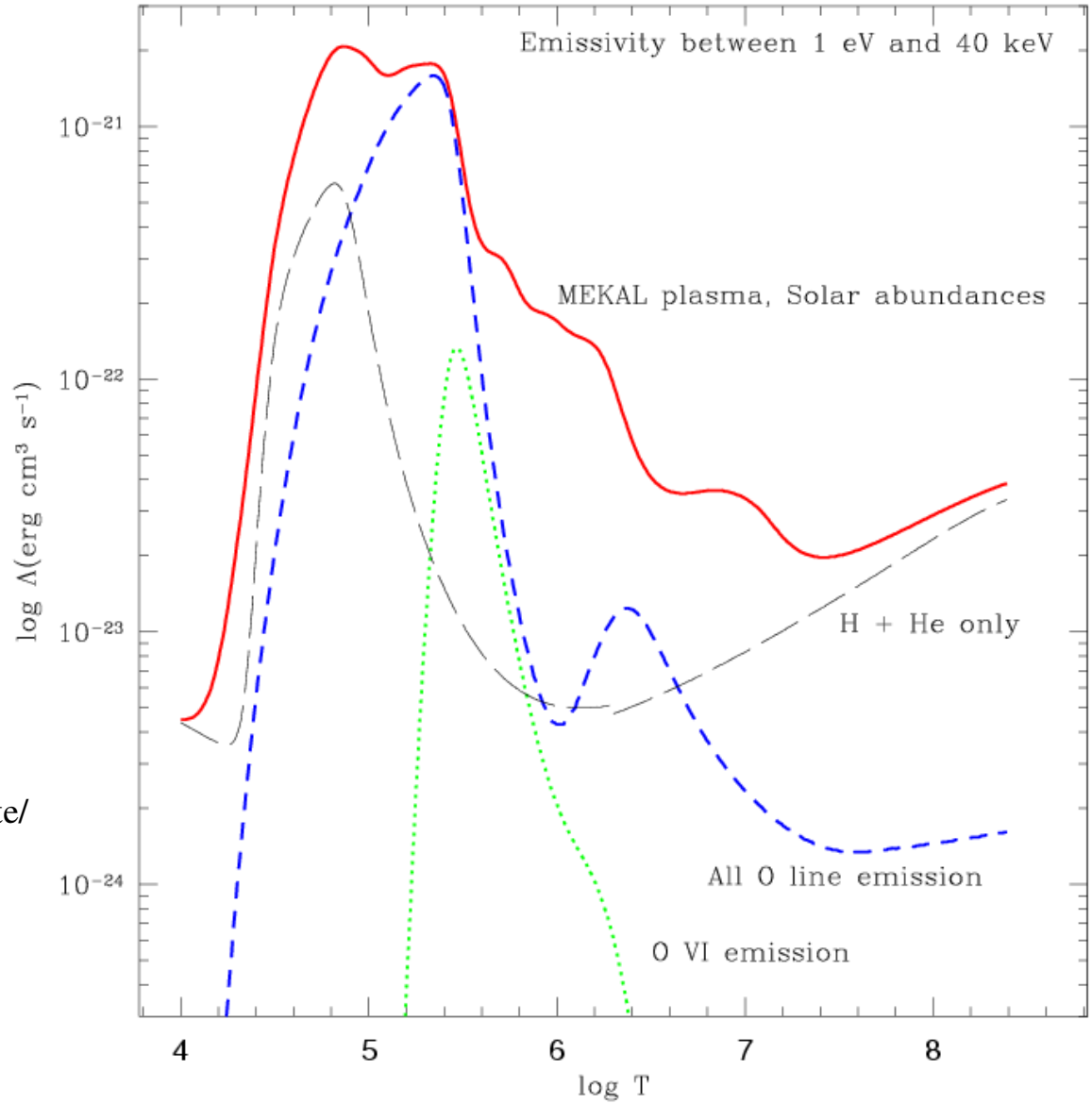
OVII, OVIII, Ne IX Kα lines.

Find columns of OVII lines 10^{16} cm^{-2}, giving (see ionization equilib slide above)

$N_H \sim 10^{19}$ cm^{-2} ~ 0.003cm^{-3} x 2kpc.

Hot Gas

Solar abundance gas in collisional equilibrium.
Comparison of total cooling emissivity (red), and contributions to that cooling emissivity from all oxygen ions and lines (blue), and the OVI 1032+1038 lines alone (green).
From Dave Strickland
XSPEC and
coolcurve_create codes.
http://proteus.pha.jhu.edu/~dks/Coolcurve_create/



Hot gas -Xrays

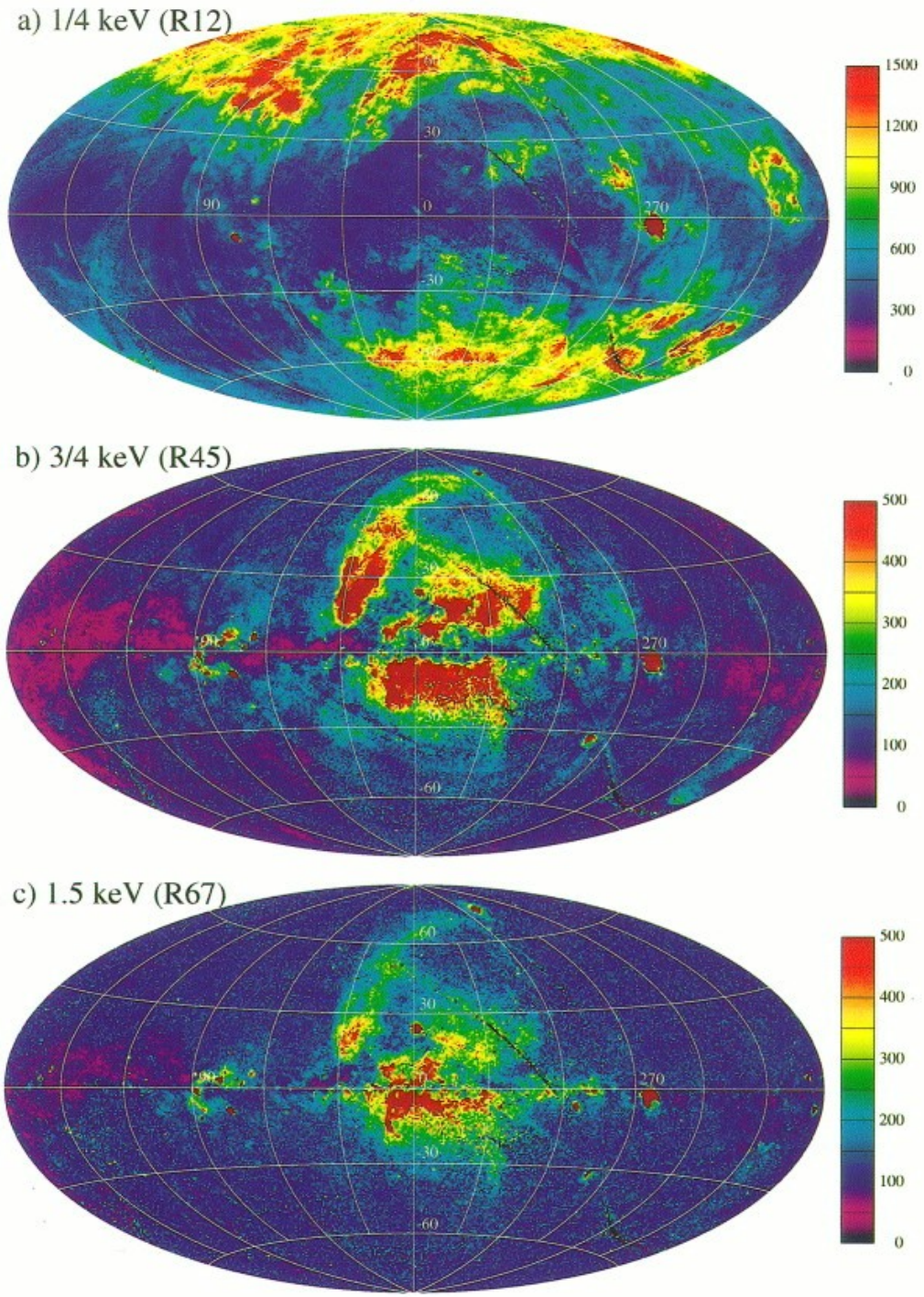
Fron ROSAT all-sky survey
Snowden et al 1997 ApJ 485, 125

X-ray absorption cross-section of ISM scales roughly as $E^{-8/3}$, where E is X-ray photon energy.

At 0.25keV, optical depth unity produced by $N_H=10^{20}$ cm^{-2}. So mean free path is about 100pc. Emission is just from the local hot gas bubble in which the sun lives

At 0.75 keV, optical depth unity produced by by $N_H=1.5x10^{21}$ cm^{-2}. So mean free path is about 1.5kpc in the plane.

At 1.5keV, the X-rays can penetrate most of the galaxy.



Inferences from X-ray emission

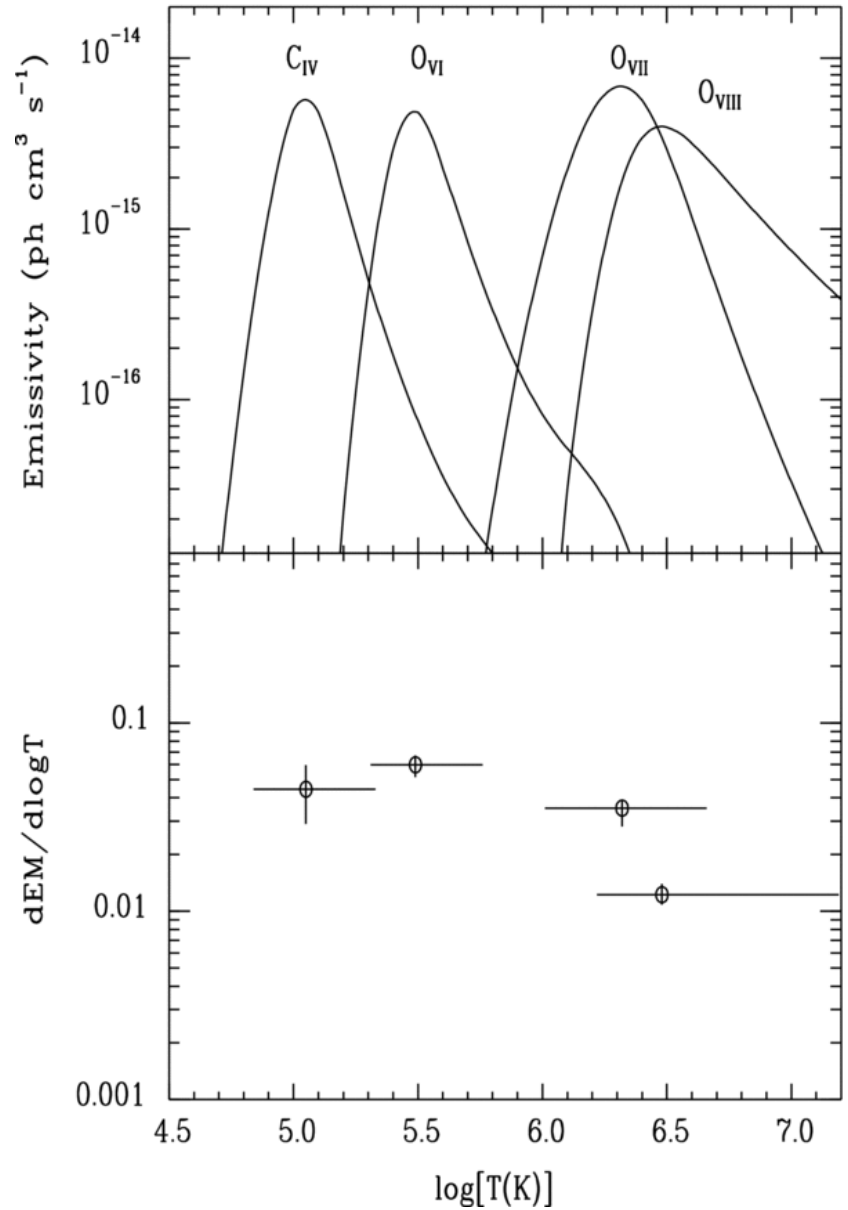
Typical hot gas emission from gas in the Galactic *bulge* <5kpc radius (NOT disk! NOT solar neighborhood) with

density 0.003 cm^{-3}.
Scale height 2kpc
Temperature $4x10^6$ K.
Pressure nT=p/k=30,000 cm^{-3} K (about 10 times disk pressure near sun)
Total luminosity $2x10^{39}$ erg/s.
Total mass $3x10^7$ Msun.

Known to be well inside solar circle because of shadow cast by molecular cloud complex at ~3kpc distance. Half of 0.5-2keV emission from beyond that cloud complex (Park et al 1997 ApJ 476, L77).

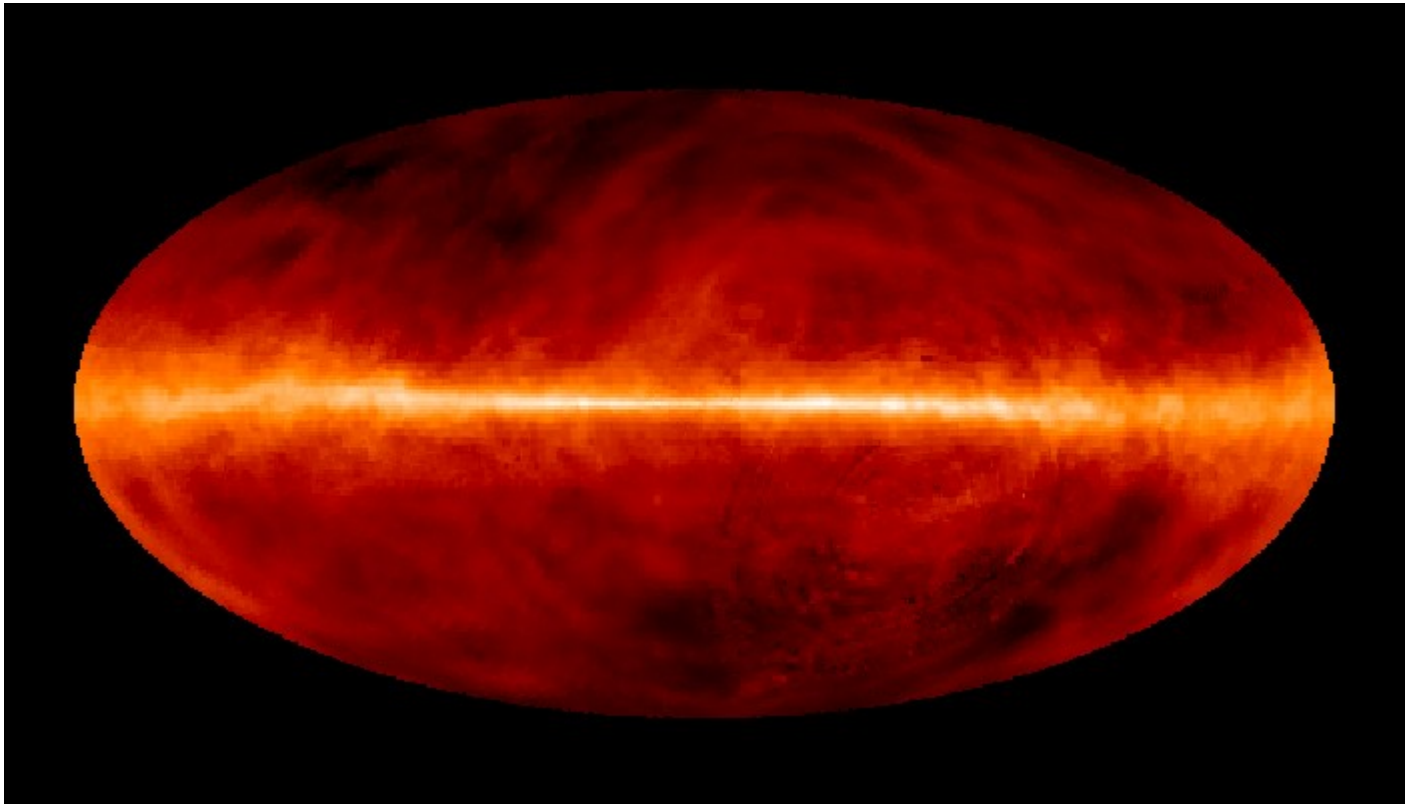
See also S. Lei et al 2009 ApJ 699, 1891.

Hot Gas -Line emissivity



From Lei, Shelton & Henley 2009
ApJ 699, 1891

Neutral Hydrogen emission, 21cm line



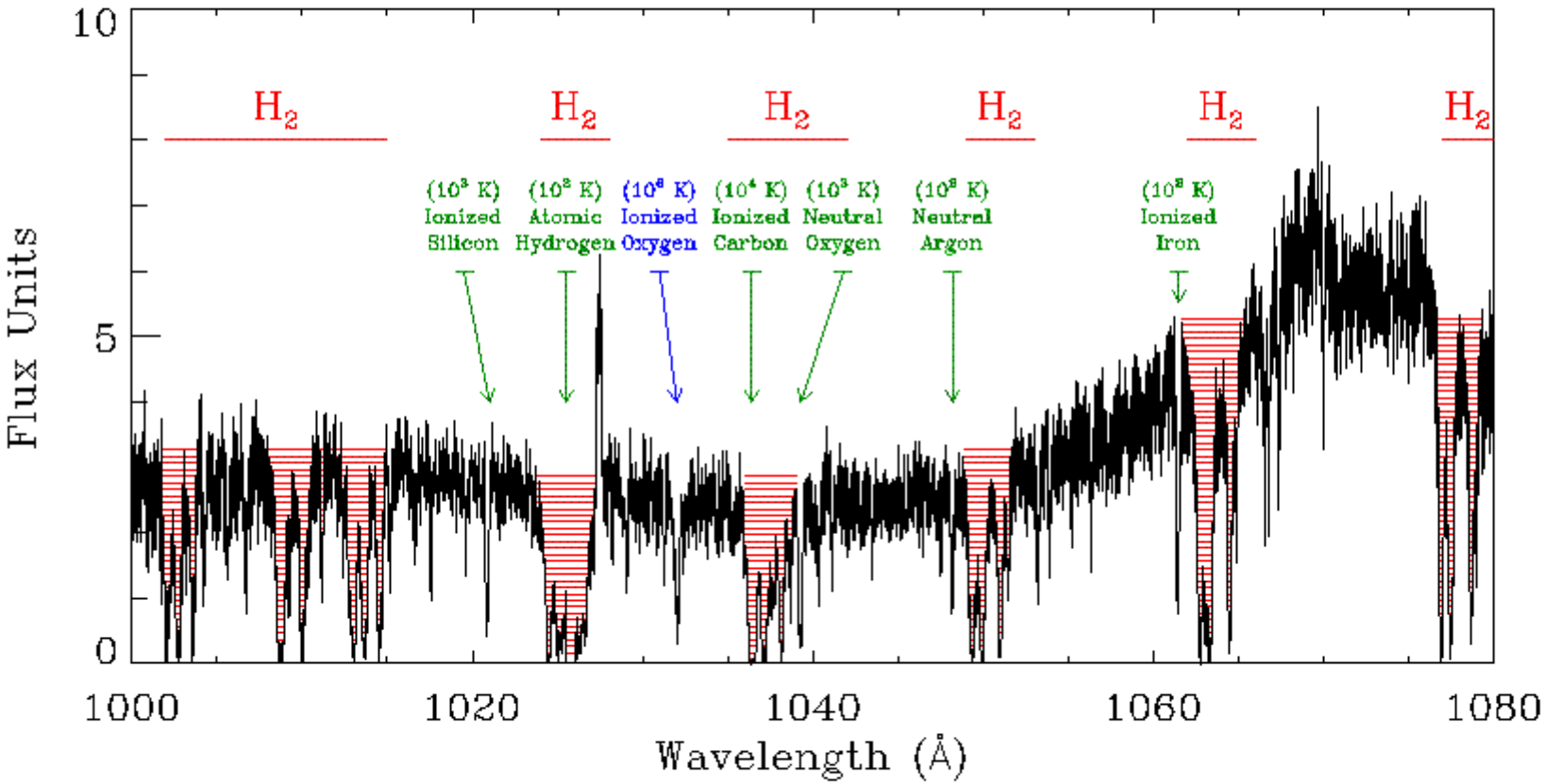
Color represents radio brightness temperature = optically thin column density of neutral hydrogen, from 21cm, 1420MHz hydrogen hyperfine transition. apod010113

Giant shells of HI surround X-ray emitting hot gasbubbles (e.g. North Polar spur, Eridanus shell). Also 10^5 Msun, 50pc clouds around molecular clouds, star forming regions (e.g. Orion, Monoceros)..

$$N_{HI} = 2\times 10^{18}\,\mathrm{cm}^{-2} \int \frac{T_b}{K} \frac{dv}{\mathrm{km\ s}^{-1}}$$

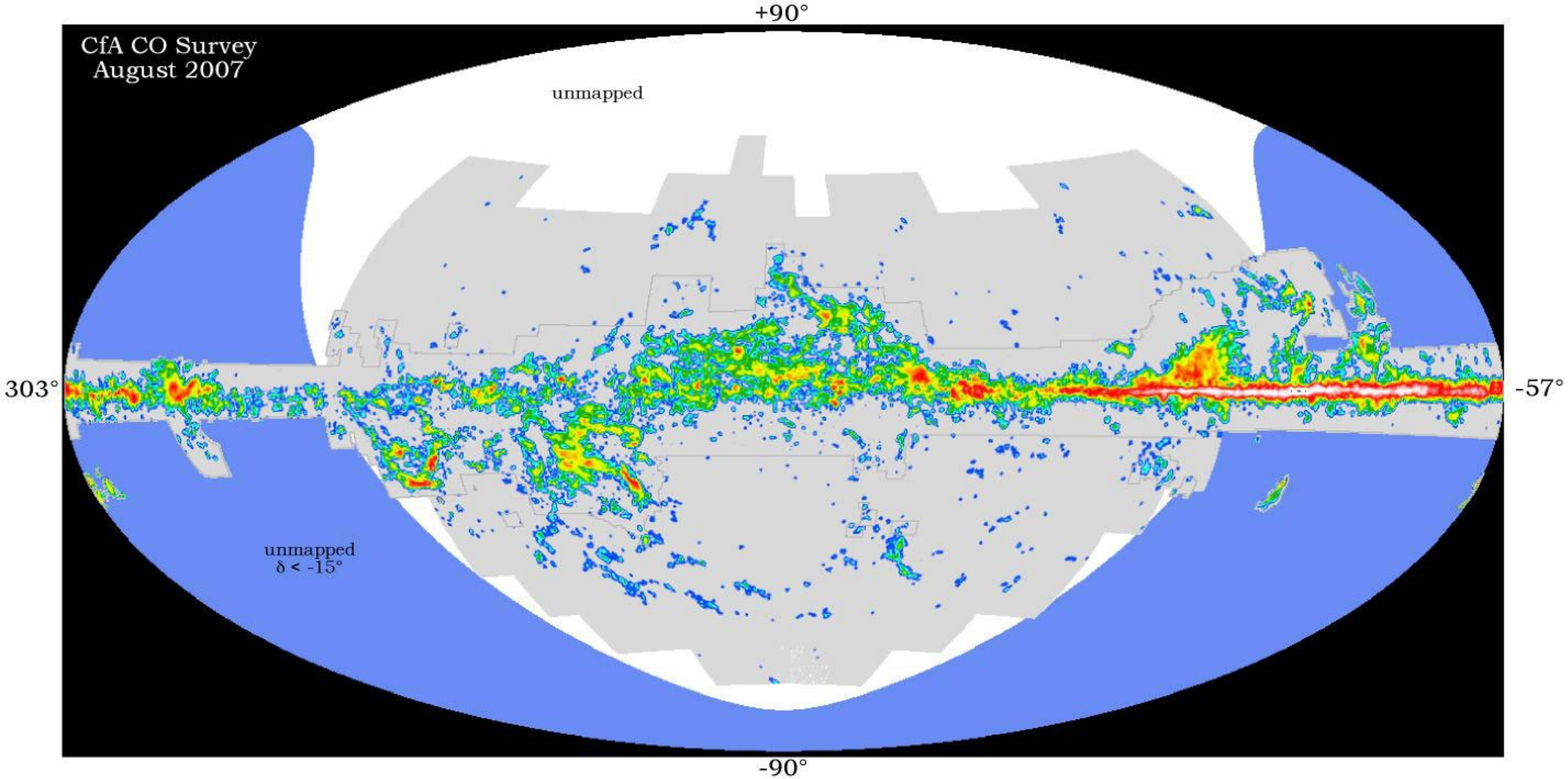
Absorption spectroscopy: hot, warm, cold gas

- Molecular Hydrogen -- Raw Material for Forming Stars
- Cold Interstellar Gas -- Atomic Gas Before Compression
- Hot Interstellar Gas -- Results of Explosive Heating



FUSE spectrum of quasar E141-G55, showing Milky Way (z=0) absorption lines from Shull & Tumlinson cf Shull et al 2000 ApJ 538, L73

Cold, dense gas



H_2 has no dipole moment. Recently studied in UV absorption along a few lines of sight. For emission maps, use CO (dipole!) as tracer. But CO/H_2 can be tricky.

Molecules form in cold gas!

Cummins, Linke & Thaddeus
1986 ApJS 60, 819
A survey of the mm-wave spectrum of Sgr B2.
70-150 GHz, 1MHz resolution.
457 lines of 21 molecules.

Small piece of the spectrum shown at right.

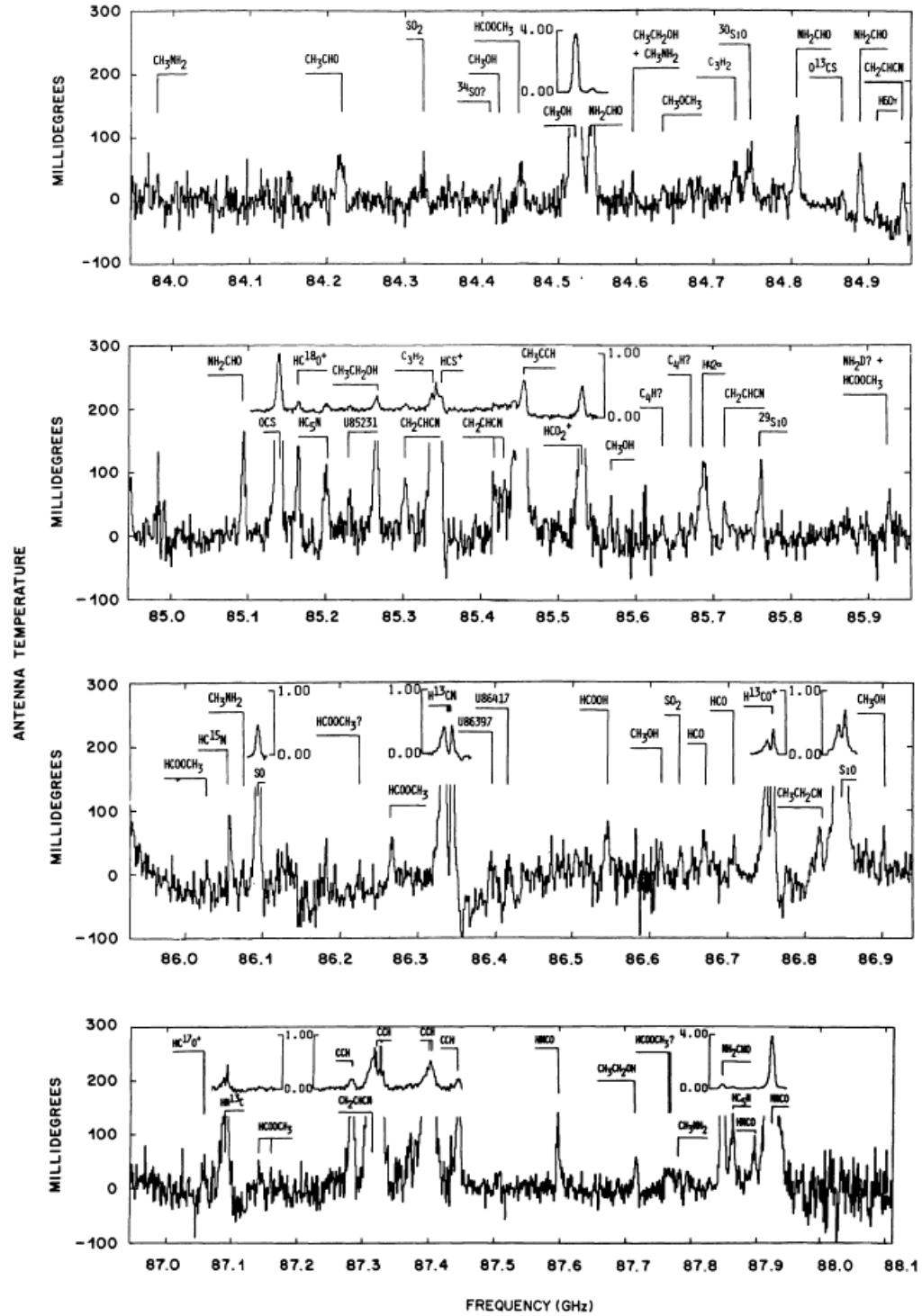


FIG. 7—*Continued*

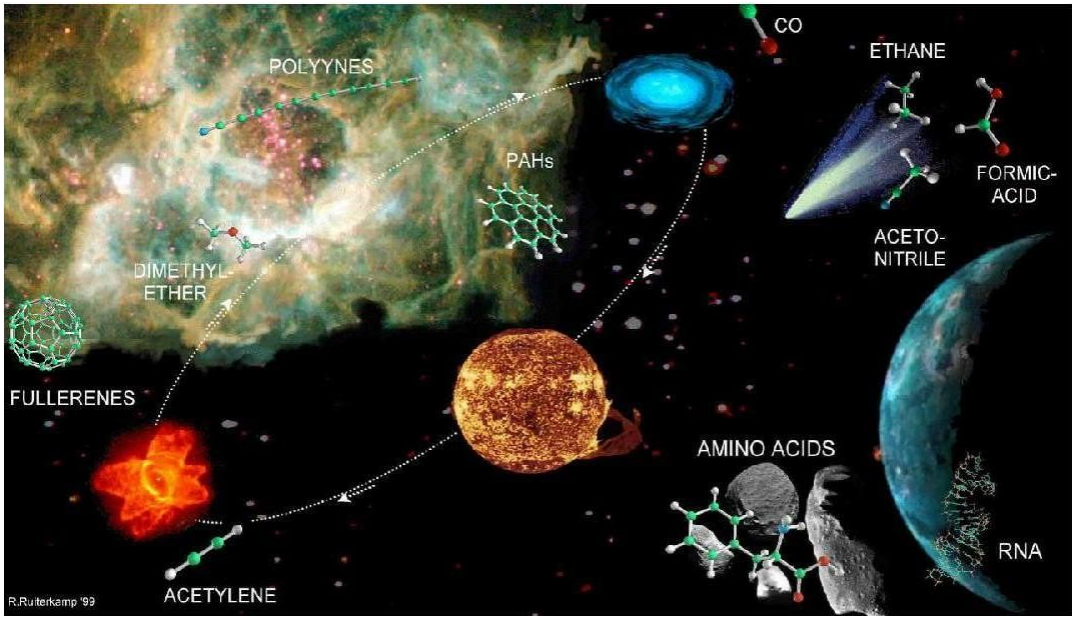
Chemistry in cold, dusty gas

THE ASTROPHYSICAL JOURNAL, 196:L99–L102, 1975 March 15

DETECTION OF INTERSTELLAR *TRANS*-ETHYL ALCOHOL

B. ZUCKERMAN*
University of Maryland
B. E. TURNER
National Radio Astronomy Observatory,† Charlottesville

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.



For a reasonably complete list,
see wikipedia
"List of molecules in interstellar space"
Dust is an important catalyst.

Other constituents of ISM 1-B field

- Recall pressure in B field, cosmic rays, turbulence all comparable to thermal gas pressure
- Magnetic field ~5 μG in diffuse gas, higher in molecular clouds
- Diagnostics of B field:

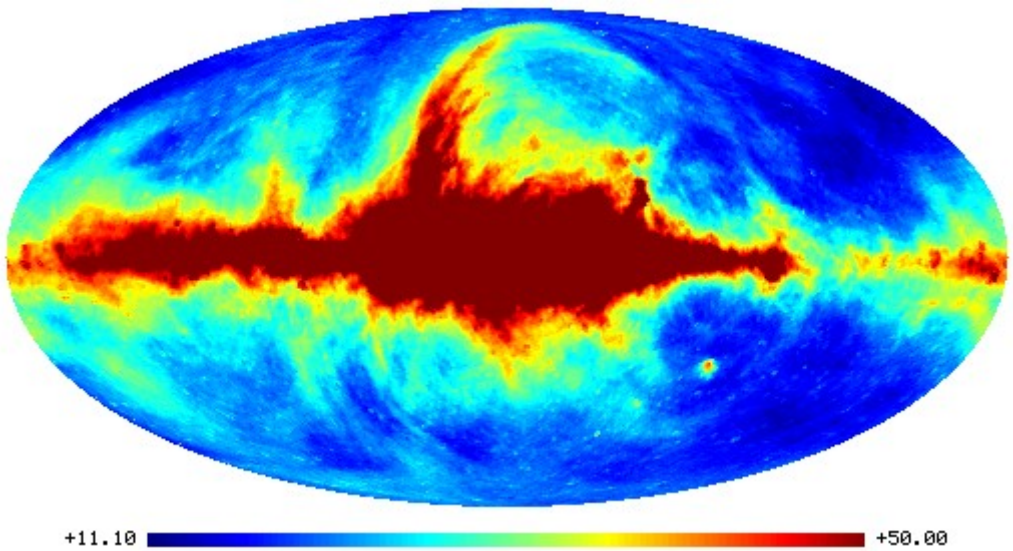
$$\mathrm{RM} = \int n_e B\, dl$$

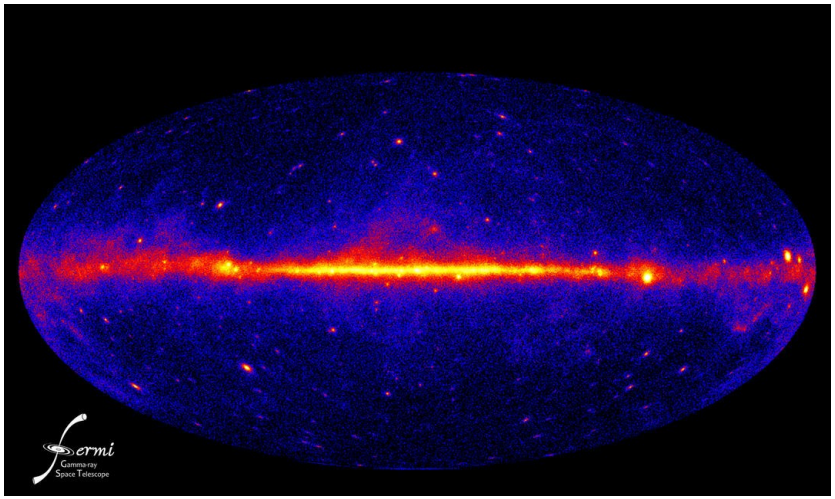
  - Pulsar Faraday rotation of polarization (Rotation Measure)
  - Zeeman splitting of 21cm, OH, H_2O lines (splitting less than Doppler width unless B>mG).
  - (electron synchrotron radiation)
  - (Dust grain alignment)

Importance of the B field

- Seeded by stellar winds
- Grown by a dynamo using Galactic differential rotaiton and buoyant circulation driven by cosmic rays and supernova-heated hot gas. Mixed by supernova, stellar wind-driven turbulence.
- Prevents cloud collapse, regulates accretion, and thus star formation.
- Determines cosmic ray propagation and diffusion.

Other constituents 2 -Cosmic rays

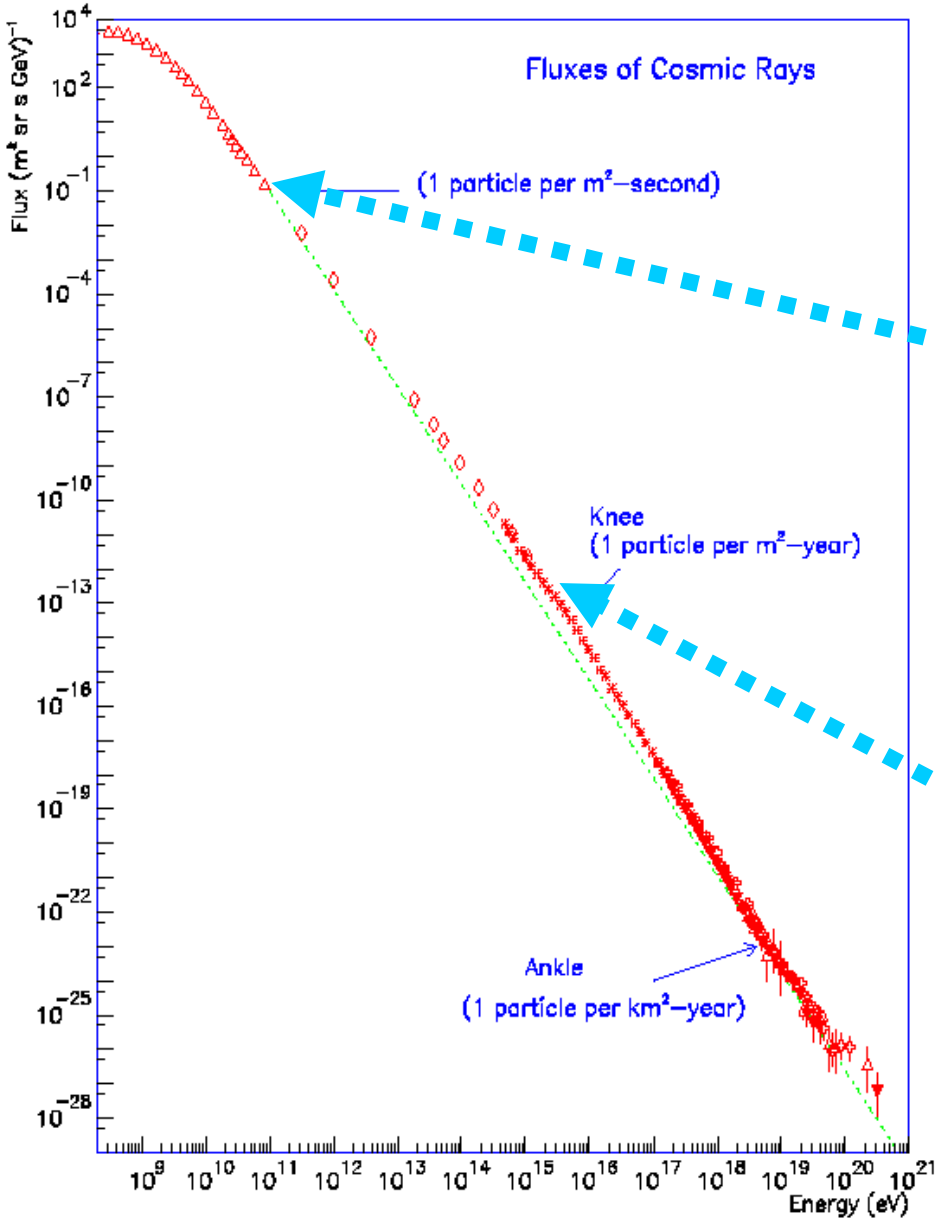


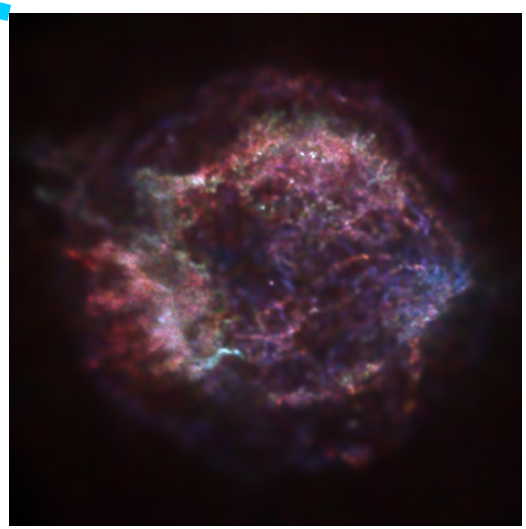


408MHz synchrotron radiation from cosmic ray electrons with $\gamma \sim 10^4$ in the galactic magnetic field.

Fermi 1-year >0.3-10 GeV gamma-ray image. Dominant source (low lats) is pp -> π^0 -> $\gamma\gamma$. Also some bremsstrahlung (low lats) and inverse compton scattering (high lats) from cosmic ray electrons.

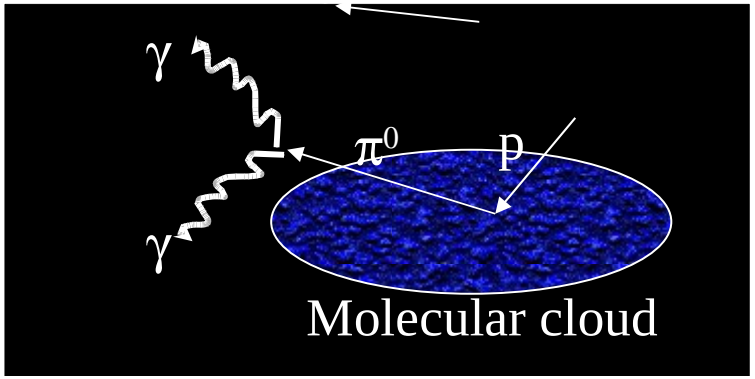
Local cosmic ray spectrum and acceleration in SNR shocks



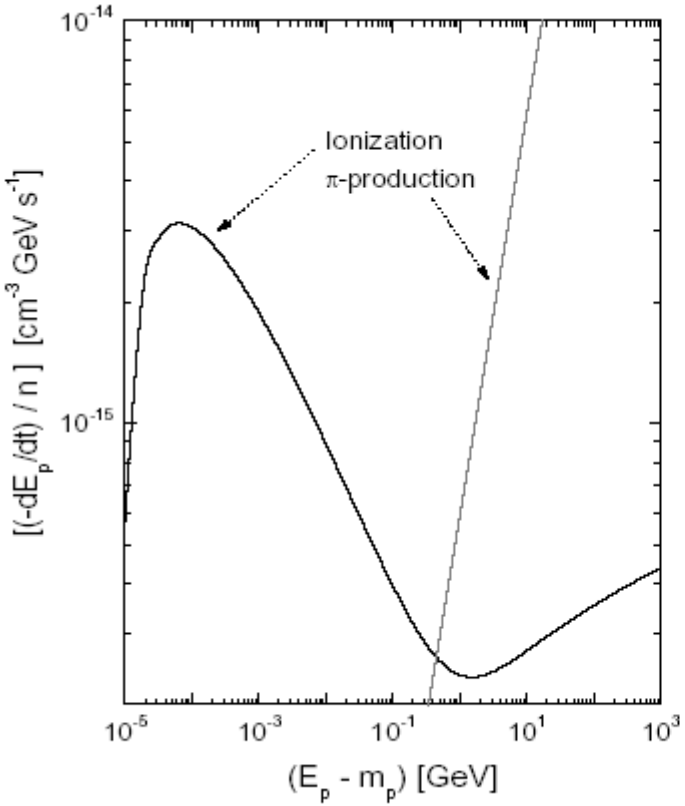


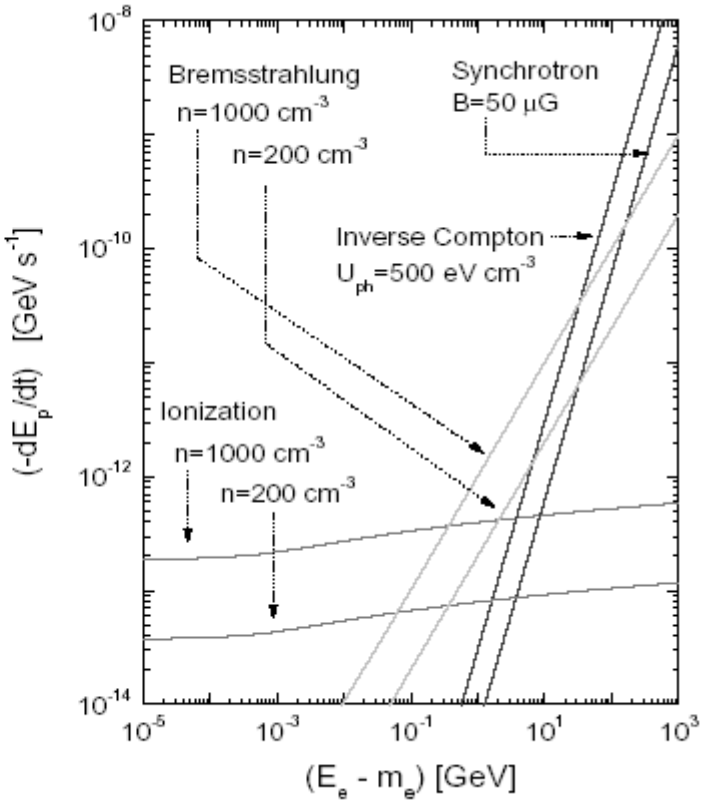
E.S. Phinney, Ay 126, Jan 5 2009

Cosmic ray energy losses



or radio





Note that cosmic rays do not propagate in straight lines: they gyrate about irregular magnetic field lines: *diffuse*!

Importance of cosmic rays

- Unlike photons, can propagate into dense molecular clouds
- Ionize clouds and other regions shielded from ionizing photons.
- Heat those regions
- Keep them ionized enough to couple to magnetic field, and thus regulate collapse and accretion, star formation.

Energy input to cosmic ray acceleration

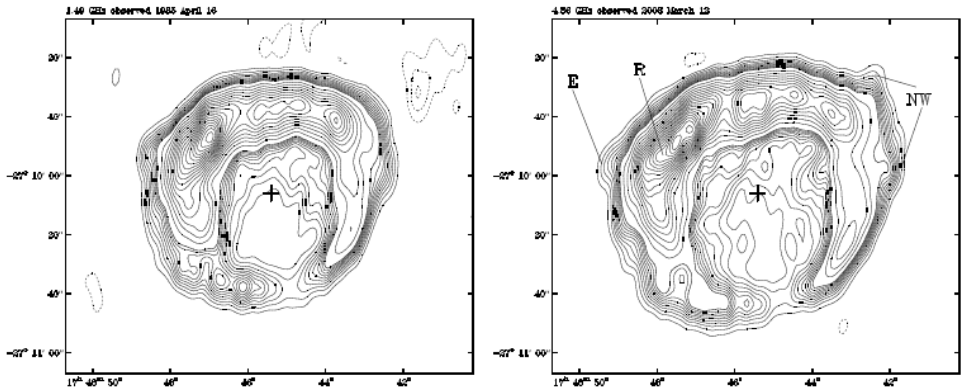
- Cosmic rays diffuse: scattered by irregularities in the magnetic field
- Eventually escape the Galaxy
- While propagating, heavy (C,O, etc) CRs collide with protons, and spall to rare isotopes (Be, B, etc)
- Abundance of spallation products implies CRs traverse X~ 7 g cm^{-2} of protons before they escape. This gives energy input estimate.

$$X = \bar{\rho}\, c\, \tau$$

$$L_{CR} = \frac{3\mathrm{p}_{CR} V_{CR}}{\tau} = \frac{3\, p_{CR} V_{CR} \bar{\rho}\, c}{\bar{\rho}\, c\, \tau} = \frac{3\, p_{CR} M_{gas}\, c}{X} = 1.5 \times 10^{41}\ \mathrm{erg\ s^{-1}}$$

approx 20% of supernova kinetic energy input to ISM!

Powering the ISM 1: supernovae



1985 2008

Inferred rate: about 1 per 50 years in Galaxies like Milky Way. We must miss seeing most!

1Msun@10,000km/s=10^{51} erg every 50 years = 6×10^{41} erg/s energy input to ISM.

G1.9+0.3 youngest known galactic supernova remnant expanding 0.65%/year so <150 years old

Reynolds et al arXiv:0804.1487

1985 and 2008 radio images: Green et al arXiv:0804.2317

1.5-6keV hard X-ray 5GHz radio

from Reynolds et al arXiv: 0903.1870

Historical supernovae:

185 (G315.4-2.3)

1006 (PKS1459-41)

1054 (Crab)

1181 (3C58)

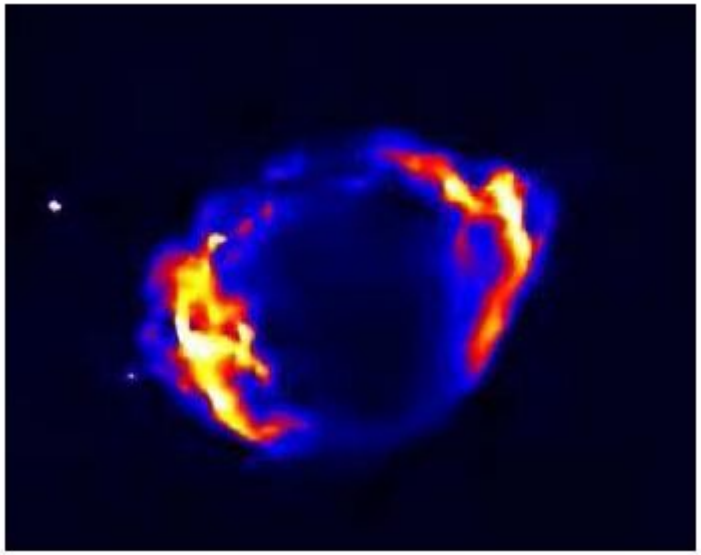
1572 (Tycho)

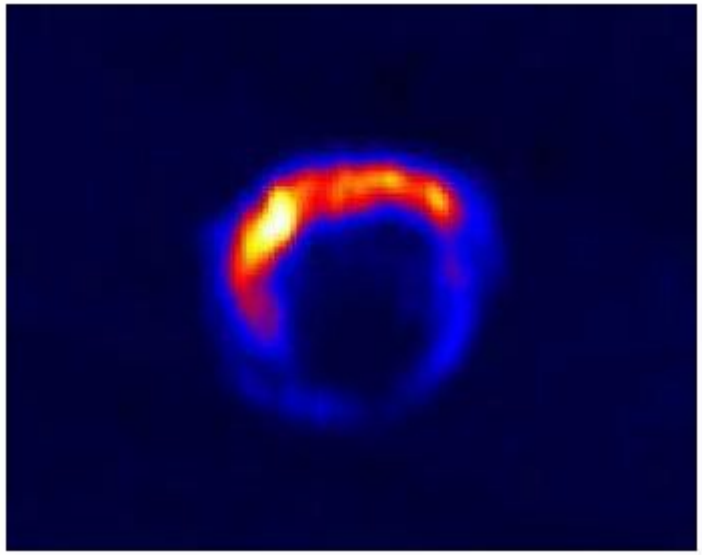
1604 (Kepler)

1680?? (Cas A)

missed this one!

1987A (LMC)



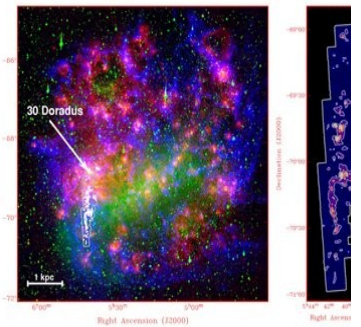


Powering the ISM -2: stellar winds

- Provide ~90% of the mass input to the ISM (>10x more than supernovae), about a solar mass per year.
- Provide ~50% of the momentum input to the ISM (comparable to supernovae)
- Provide ~10% of the kinetic energy input to the ISM (supernovae provide 90%).
- Since young stars stay close to their birthplaces, they are especially important for star forming regions.

Powering the ISM 3: photons

- Optical photons -luminosity is about 100 times supernova kinetic energy input.
  - Mostly just heats dust grains, which then radiate thermal infrared radiation, which escapes to intergalactic space.
  - Only very weak dust->gas heating in diffuse ISM. So despite dominating the luminosity, doesn't affect ISM much.
- UV photons <13.6eV: photodissociate molecules
- UV photons >13.6eV: ionize hydrogen
  - Mostly absorbed in dense HII regions. Pressure -> shocks.
  - Some escape into diffuse gas, tranforms WNM to WIM.



blue: HI
red: Hα (HII)
green: R band
30 Doradus
star forming
region in
LMC

Summary of phases of the ISM

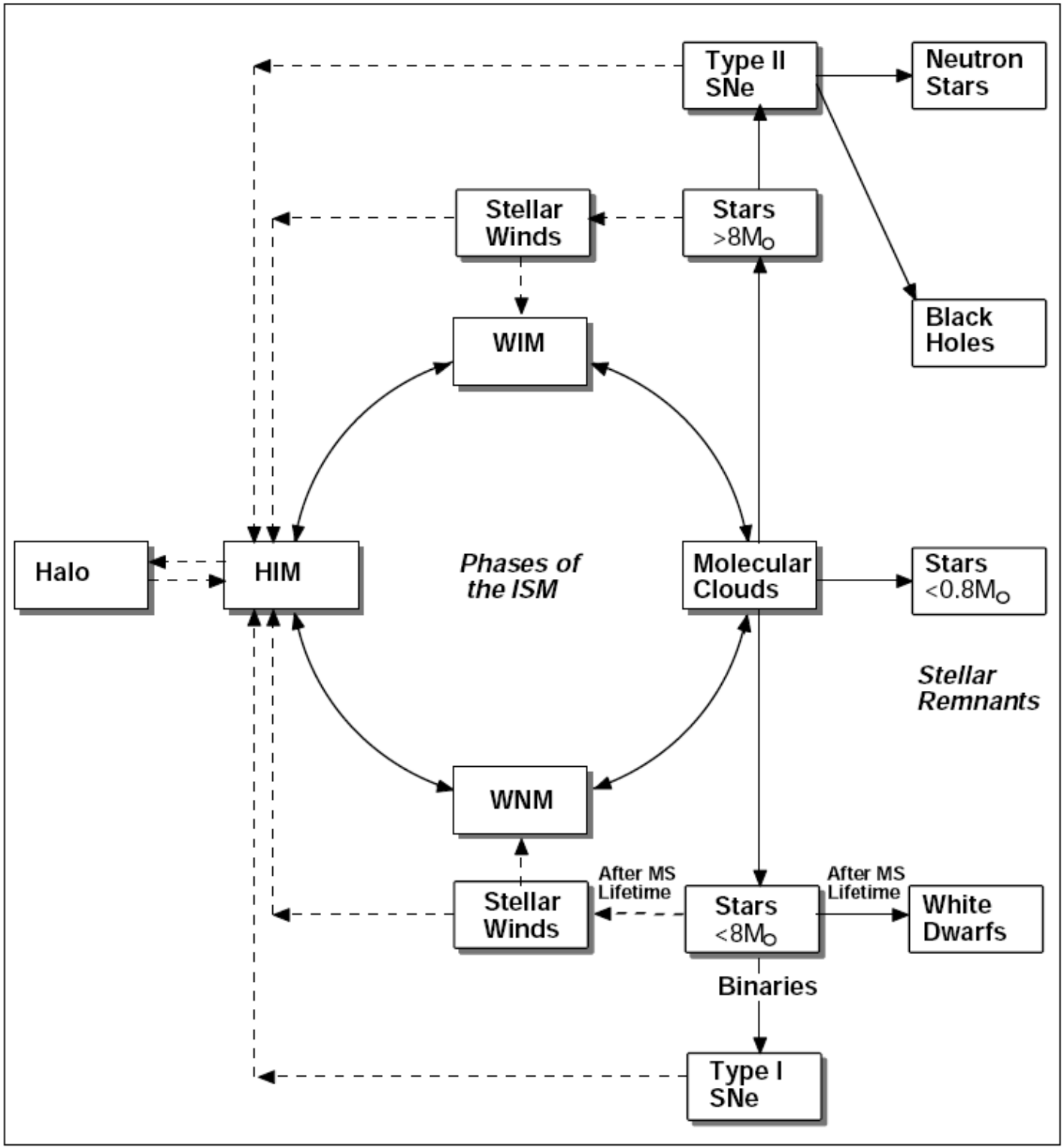
- Magnetic field
- Cosmic Rays
- Photons
- Gas -see next page

- Molecular Clouds
  - $\phi_V \sim 1\%$, $\phi_M \sim 12\%$, 10K, >200cm^{-3}
- Cold Neutral Medium (CNM)
  - $\phi_V \sim 1\%$, $\phi_M \sim 25\%$, 80K, 50cm^{-3}
- Warm Neutral Medium (WNM)
  - $\phi_V \sim 25\%$, $\phi_M \sim 35\%$, 8000K, 0.5cm^{-3}
- Warm Ionized Medium (WIM)
  - $\phi_V \sim 25\%$, $\phi_M \sim 25\%$, 8000K, 0.25cm^{-3}
- Hot Ionized (intercloud) Medium (HIM)
  - $\phi_V \sim 50\%$, $\phi_M \sim 4\%$, 2×10^6K, 0.002cm^{-3}

Cycles of matter and energy

- Mass ejected from stellar winds and supernovae enriches ISM with heavy elements, changing cooling, and forms new stars.
- Cosmic rays created in supernovae at the end of lives of stars ionize the deep interiors of dense clouds, catalysing chemistry that enhances cooling so that they can form stars and coupling them to B.
- Inputs of momentum and energy from young stars prevent clouds from collapsing, regulating the birth rate of stars.

The star-gas cycle in the ISM. From Dopita & Sutherland 1999, *Diffuse Matter in the Universe.*



ISM in dynamic quasi-equilibrium

- Mean heating balances mean cooling
  - Exchanges of mass between phases roughly balance
- Gas outflow balances cooling inflow
- Star formation balances mass inputs (with steady sink to <1Msun stars).
- Supernovae create hot gas (HIM), cosmic rays
- SN, stellar winds, HII region shocks compress gas -cool to molecular clouds
- Regulation of star formation by gravitational instability

Regulation of star formation

- Global regulation -threshold for gravitational instability

Gas in a rotating disk, gas surface density Σ

Epicyclic frequency $\kappa \approx$ Rotation frequency Ω

Sound speed c_s

Self gravity tries to pull the disk together

Long wavelengths stabilized by shear, short wavelengths stabilized by pressure

Instability for intermediate wavelengths if $G\Sigma > \frac{c_s}{\pi\kappa} \approx \frac{c_s}{\pi\Omega}$ (Toomre $Q<1$)

Seems to be observed threshold for star formation -cf

Kennicutt 1989 ApJ 344, 685; Martin & Kennicutt 2001 ApJ 555, 301

Regulation of star formation

- local regulation -efficiency and rate
  - Ambipolar diffusion (separation of neutral gas from ionized components and magnetic field) may be the rate limiting step.
  - Turbulent motions excited by newly formed stars stop collapse, and winds, HII regions and supernovae eject gas -determine limit to fraction of gas that forms stars i.e. the star formation efficiency.
    - cf. Matzner & McKee 2000 ApJ 545, 364
    - Krumholtz, Matzner & McKee 2006 ApJ 653, 361