Interstellar Medium

星際物質

http://www.astro.ncu.edu.tw/~wchen/Courses/ISM/index.htm

Interstellar Medium --- Syllabus

NCUIA 2025 Spring

Prof. Wen-Ping Chen (S4-906; ext. 65960)
Office hours: M 3 to 5 pm; Tu 3 to 5 pm; or by appointment

The course consists of two main parts:

(1) the morphological and physical characteristics of various **material components** found in the interstellar space, from extremely cold molecular gas and dust, to diffuse atomic hydrogen nebulae, to hot ionized gases around luminous stars; some of these are relevant to intergalactic media as well.

(2) interactions between stars and their environments, i.e., **between matter and radiation**.

We will discuss what has been observed, and the theories to interpret these results. The course will end by the onset within molecular clouds of formation of stars and planets. There is no prerequisite; knowledge of radiative transfer and matter-radiation interplay will be covered in the course though prior exposure should help.

* ***Textbook***: ***Physics of the Interstellar and Intergalactic Medium***,
by Bruce T. Draine (2011, Princeton U Press)

https://www.astro.princeton.edu/~draine/

https://press.princeton.edu/books/paperback/9780691122144/physics-of-the-interstellar-and-intergalactic-medium

NCU library carries an online version of this book,
https://ebookcentral.proquest.com/lib/ncutw/reader.action?docID=664587&query=&ppg=1

* ***Subjects:*** gaseous nebulae and dust clouds; radiative processes; radiative transfer, photoionization; Strömgren spheres; stellar winds; circumstellar disks and star formation; galactic magnetic fields: Zeeman effects; polarization

  Primary reference: *Interstellar Processes* by D.J. Hollenbach & H. A. Thronson, Jr. (Reidel) --- A close look at our Milky Way Galaxy, including its morphology, stellar content, stellar population, kinematics and dynamics.

* ***Subjects:*** 21-cm line observations; giant molecular clouds; stellar population; initial mass function; galactic kinematics and dynamics; the Galactic center

  Primary reference: *Galactic Astronomy* by D. Mihalas & J. Binney (Freeman)

There will be homework assignments, and perhaps term projects. This is a fast growing subject. In addition to "standard" textbook problems, there may be questions for which I do not know the answers myself (hardly surprising). For these, you will need to consult research literature.

Grading is based on homework (~40%), the mid-term (~30%) and final (~30%) exams.

The following references are potentially useful:

- ✓ *Physics of the Interstellar Medium,* by Dyson & Williams (eBook)
- ✓ *The Milky Way as a Galaxy,* by Gilmore, King, & van der Kruit
- ✓ *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei,* by Osterbrock
- ✓ *The Galactic Interstellar Medium,* by Pfenniger & Bartholdi
- ✓ *The Interstellar Medium in Galaxies,* ed. By Thronson & Shull
- ✓ *Gaseous Nebulae,* by Aller
- ✓ *The Galactic Interstellar Medium,* by Burton, Elmegreen, & Genzel
- ✓ *Physics of the Galaxy and Interstellar Matter,* by Scheffler & Elsässer
- ✓ *Physical Processes in the Interstellar Medium,* by Spitzer (eBook);
  New 2008 version https://onlinelibrary.wiley.com/doi/epdf/10.1002/9783527617722
- ✓ *The Physics and Chemistry of the Interstellar Medium,* by Tielens
- ✓ *Physics and Chemistry of the Interstellar Medium,* by Kwok
- ✓ *Interstellar Matters,* by Verschuur
- ✓ *Galactic Nebulae and Interstellar Matter,* by Dufay
- ✓ *Physics of Interstellar Dust,* by Krügel (eBook)
- ✓ *Dust in the Galactic Environment,* by Whittet
- ✓ *The Dusty Universe,* by Field & Cameron

The following are useful general references, not necessarily specific to ISM/MW:

- ✓ *Astrophysics II,* by Bowers & Deeming
- ✓ *Stars, Nebulae, and the Interstellar Medium,* by Kitchin
- ✓ *Atoms, Stars, and Nebulae,* by Aller
- ✓ *The New Cosmos,* by Unsöld & Baschek

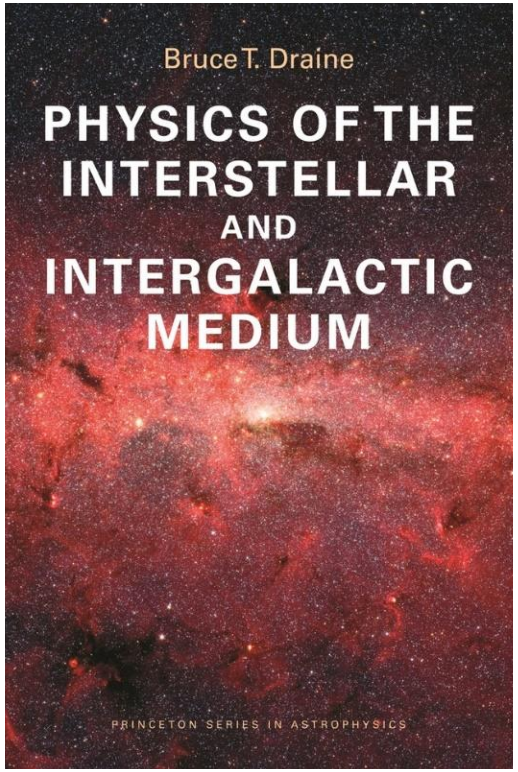
“ISM” Class Schedule 2025 Spring

#	Date	
01	02/20	
02	02/27	No class*; Chile
03	03/06	30 min extra
04	03/13	30 min extra
05	03/20	30 min extra
06	03/27	
07	04/03	Holiday
08	**04/10**	**Midterm Exam**

#	Date	
09	04/17	30 min extra
10	04/24	No class*; Mexico
11	05/01	30 min extra
12	05/08	30 min extra
13	05/15	
14	05/22	
15	05/29	
16	**06/06**	**Final Exam**
17	06/13	Exam review; suppl.

* *Instructor business leave*

The Book by Prof Bruce Draine



- An overall good book to study or to reference to
- A total of 42 chapters; first 6 on basic physics; later chapters on astrophysical applications
- With extensive (and up-to-date) appendices
- Using cgs and standard astronomical units
- Wavelength in Ångstroms in vacuo, i.e., shifted by 1Å , e.g., [OIII] doublet at 4960, 5008, rather than at 4959 and 5007 in air
- https://www.astro.princeton.edu/~draine/book/index.html has an updated errata document, problem sets, etc.

Contents

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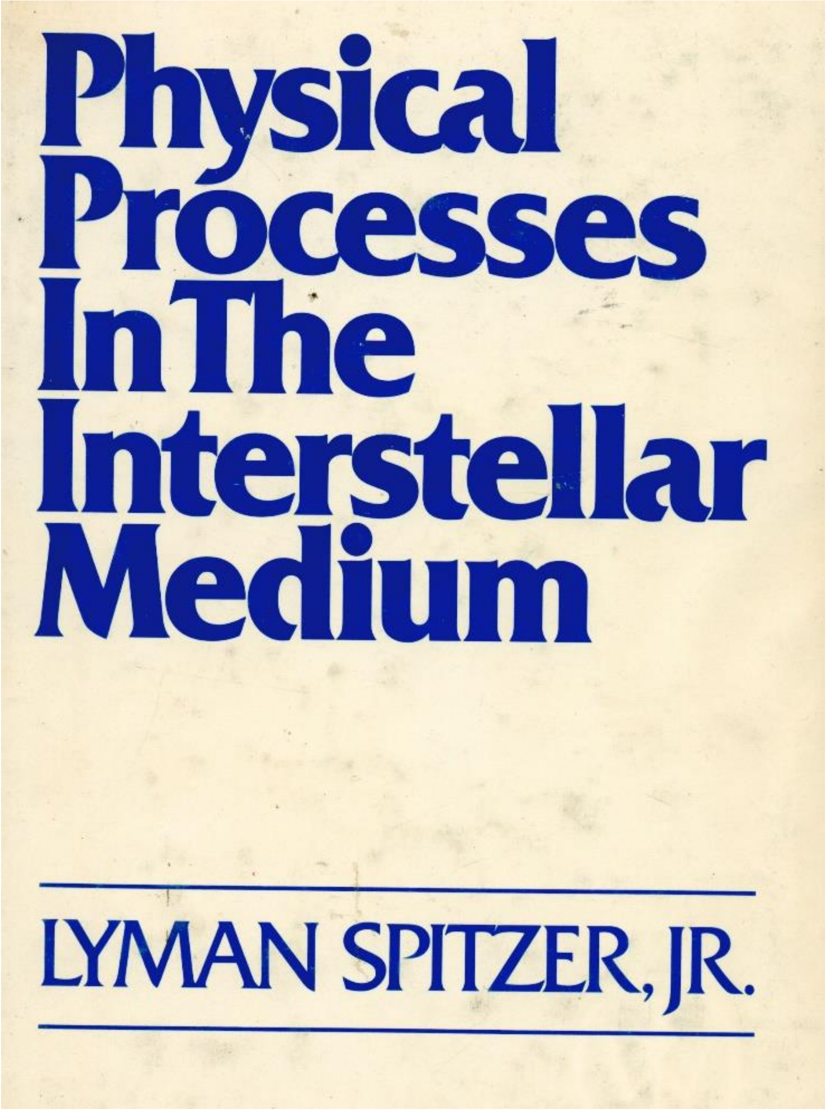

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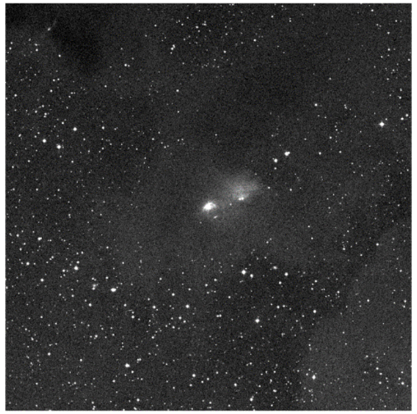
https://onlinelibrary.wiley.com/doi/pdf/10.1002/9783527617722

How to infer the existence of ISM?

Interstellar Medium (ISM)



- 1811 William Herschel "*holes in the starry sky*"
- 1904 J. F. Hartmann "*stationary*" calcium lines in the spectroscopic binary δ Orionis → of interstellar origin
- 1919 E. E. Barnard catalog of dark nebulae
- Photography → emission and reflection nebulae; dark clouds
- 1926 Sir Arthur Eddington lectured "*Diffuse Matter in Space*"
- 1927 Otto Struve "Interstellar Calcium"
- 1930 Robert J. Trumpler: absorption ↗ as distance ↗ → beginning of ISM as a new branch of astronomy

1904

INVESTIGATIONS ON THE SPECTRUM AND ORBIT OF δ *ORIONIS*.[1]

By J. Hartmann.

One of the first results obtained by M. Deslandres with the new spectrograph attached to the 62 cm refractor of the observatory at Meudon was the discovery of the "oscillation" of δ *Orionis*. I use the term "oscillation" in place of the ponderous expression "variability of velocity in the line of sight;" but the idea of oscillation is still somewhat broader, as it includes every sort of periodic variation in the spectrum, without saying anything as to its explanation.

After the publication[2] of the discovery mentioned, which was communicated to the Paris Academy on February 12, 1900, Director Vogel instructed the observers in the field of stellar spectroscopy at Potsdam to undertake to confirm the interesting phenomenon, and the observations made with the four different spectrographs then in use here proved beyond a doubt that δ *Orionis* belongs to the number of oscillating stars. A confirmation of the discovery was also given by three observations by Wright with the Mills spectrograph of the Lick Observatory.

Deslandres derived from his eleven observations a period of 1.92 days, and concluded that the orbit was very eccentric. The observations which I made at that time with the large Spectrograph III (with three prisms) attached to the 80 cm refractor could not, however, be brought into accord with that length of period; and since the measures showed that the star could be more advantageously observed with low dispersion, on account of the extreme diffuseness of its lines, I included it in the program of Spectrograph I (with only one prism). With this

TABLE III.

λ	No. of Plates	Mean Error	Remarks
3933.68	7	(±0.34)	*Ca;* always exceedingly weak and narrow.
4069.49	3	±0.16	
4097.49	5	0.14	*Si*
4116.28	11	0.07	*Si*
4144.94	2	0.28	
4200.42	2	0.20	$H\delta'$ according to Pickering's nomenclature.
4541.78	2	0.41	$H\gamma'$ according to Pickering's nomenclature.
4649.68	16	0.14	Probably a group; 4 tenth-meters wide.
4686.20	10	0.12	

Among the lines in Table III the calcium line at λ 3934 exhibits a very peculiar behavior. It is distinguished from all the other lines of this spectrum, first by the fact that it always appears extraordinarily weak, but almost perfectly sharp; and it therefore attracted my attention that in computing the wave-lengths collected in Table III for this particular line, the agreement between the results from the different plates was decidedly less than for the other, much less sharp lines. Closer study on this point now led me to the quite surprising result *that the calcium line at λ 3934 does not share in the periodic displacements of the lines caused by the orbital motion of the star.*

We are thus led to the assumption that at some point in space in the line of sight between the Sun and δ *Orionis* there is a cloud which produces that absorption, and which recedes with a velocity of 16km, in case we admit the further assumption, very probable from the nature of the observed line, that the cloud consists of calcium vapor. This reasoning finds a distinct support in a quite similar phenomenon exhibited by the spectrum of *Nova Persei* in 1901. While the lines of hydrogen and other elements in that spectrum led us, by their enormous broadening and displacement and the continuous changing of their form, to conclude that stormy processes were going on within the gaseous envelope of the star, the two calcium lines at λ 3934 and λ 3969, as well as the D lines, were observed as perfectly sharp absorption lines, which yielded the constant velocity of + 7 km during the whole duration of the phenomenon. I then expressed the opinion that these sharp lines probably did not have their origin in the *Nova* itself, but in a nebulous mass lying in the line of sight—a view which only gained in probability on the later discovery of the nebula in the neighborhood of the *Nova*. In the case of δ *Orionis* also it is not unlikely that the cloud stands in some relation to the extensive nebulous masses shown by Barnard[1] to be present in the neighborhood. The second calcium line at λ 3969 is con-

THE

ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME XLIX — JANUARY 1919 — NUMBER 1

ON THE DARK MARKINGS OF THE SKY
WITH A CATALOGUE OF 182 SUCH OBJECTS

By E. E. BARNARD

It would be unwise to assume that all the dark places shown on photographs of the sky are due to intervening opaque masses between us and the stars. In a considerable number of cases no other explanation seems possible, but some of them are doubtless only vacancies.

1919

PLATE I

North

Region North of Theta Ophiuchi
$\alpha = 17^h\ 13^m$, $\delta = -21°\ 0'$
Scale: $1^{mm} = 234''$

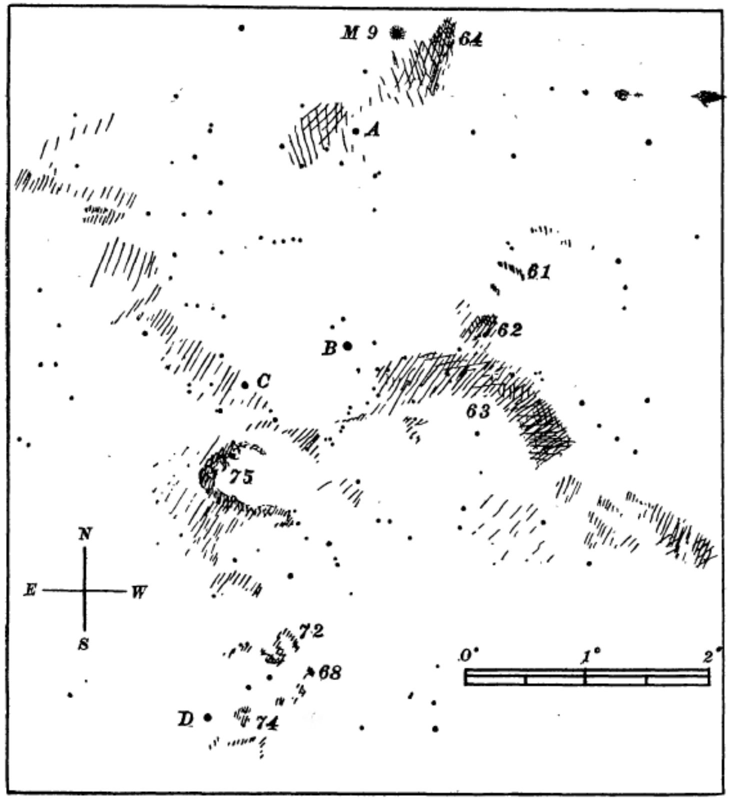


Fig. 2.—Sketch map of Plate I

Exercise

1. What is Barnard 68 (B68)?
2. Explore the image server *AladinLite* for Barnard 68.
   e.g., with DSS, PS1, 2MASS, allWISE

"So enormous is the number of stars, yet so completely incalculable are they, as to admit of their being joined with the sand upon the sea-shore, as a Figure of speech denoting a numeration which we cannot define."[1] So wrote the Reverend Thomas Milner in 1858 in his book of popular science entitled *The Gallery of Nature—A Pictorial and Descriptive Tour through Creation Illustrative of the Wonders of Astronomy, Physical Geography, and Geology.*[2] Self-explanatory titles were the rage in those days.

Lest his readers be overwhelmed by the size of the starry realm, the Reverend Mr. Milner assured that the Creator was "acquainted minutely with these multitudinous worlds, which immeasurably exceed our utmost estimates." This important point taken care of he proceeded to wax lyrical and gorgeously descriptive on the wonders of astronomy. Most noticeable in the heavens was, "That luminous celestial highway which the Greeks called the Galaxy, and the Romans the Via Lactea, from its whiteness. . . . By some of the pagan philosophers the Via Lactea was regarded as an old disused path of the sun, of which it had got tired, or from which it had been driven, and had left some faint impression of his glorious presence upon it "

MS fitting … Cepheid variables → distance

Assuming star clusters to be similar in size …

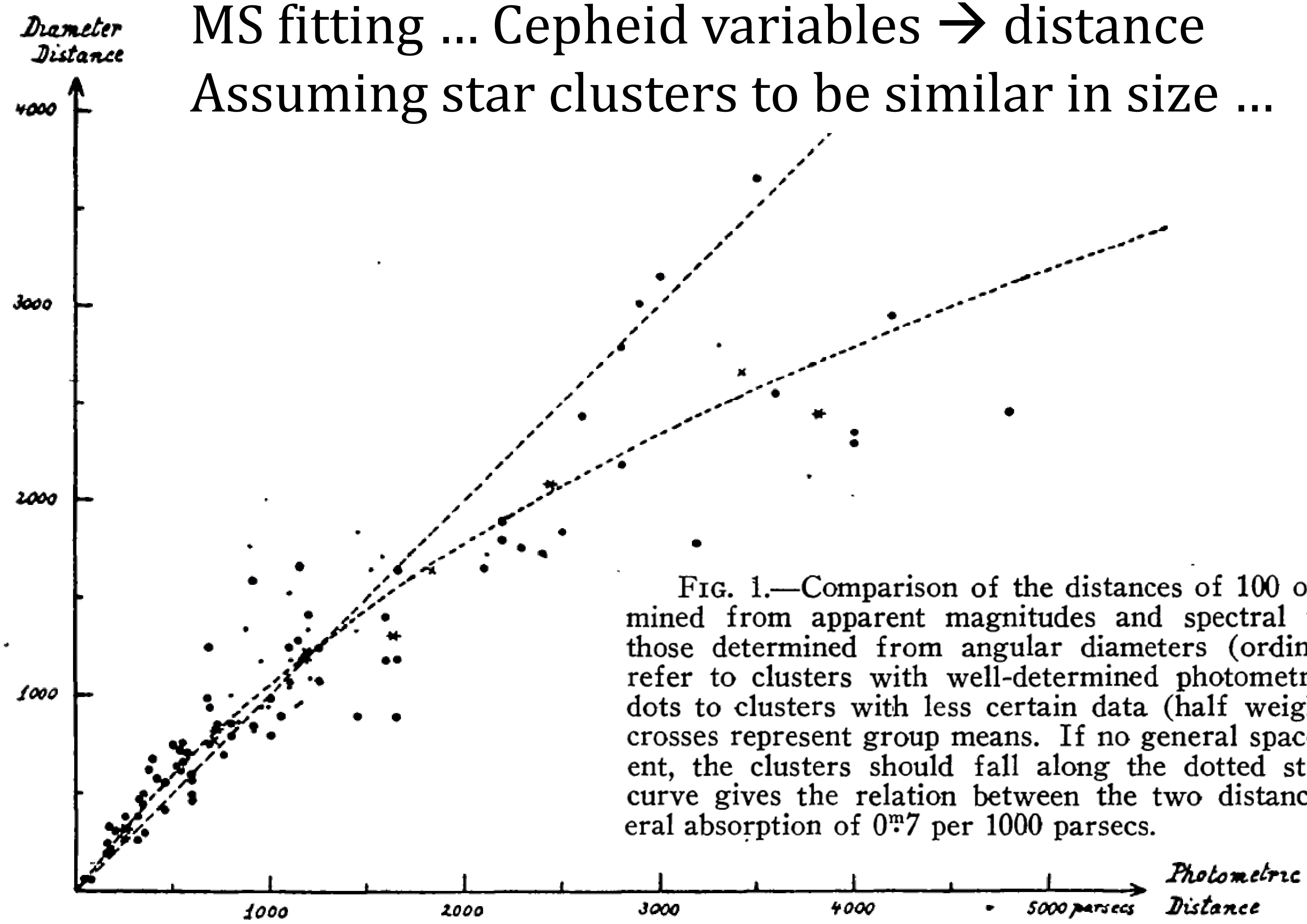
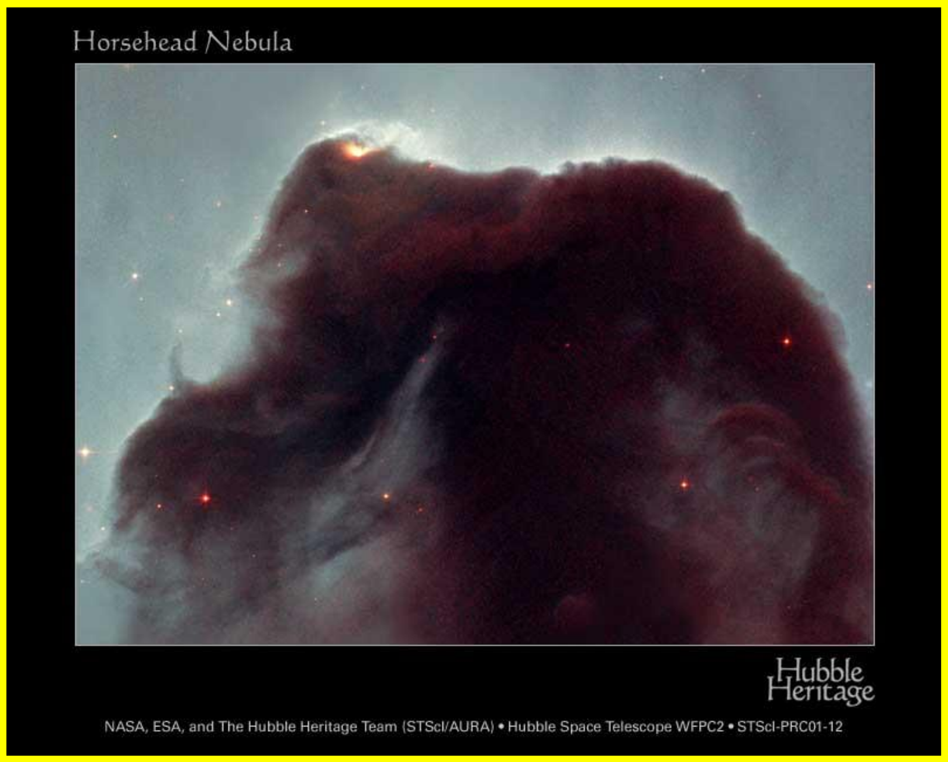


FIG. 1.—Comparison of the distances of 100 open star clusters determined from apparent magnitudes and spectral types (abscissae) with those determined from angular diameters (ordinates). The large dots refer to clusters with well-determined photometric distances, the small dots to clusters with less certain data (half weight). The asterisks and crosses represent group means. If no general space absorption were present, the clusters should fall along the dotted straight line; the dotted curve gives the relation between the two distance measures for a general absorption of $0^{m}.7$ per 1000 parsecs.

Trumpler 1930

Barnard 72 in Ophiuchus

http://www.robgendlerastropics.com/B72JMM.jpg



Star Shadows Remote Observatory

(Bok) Globules silhouetted against emission nebulosity

A dark cloud core seen against a star field

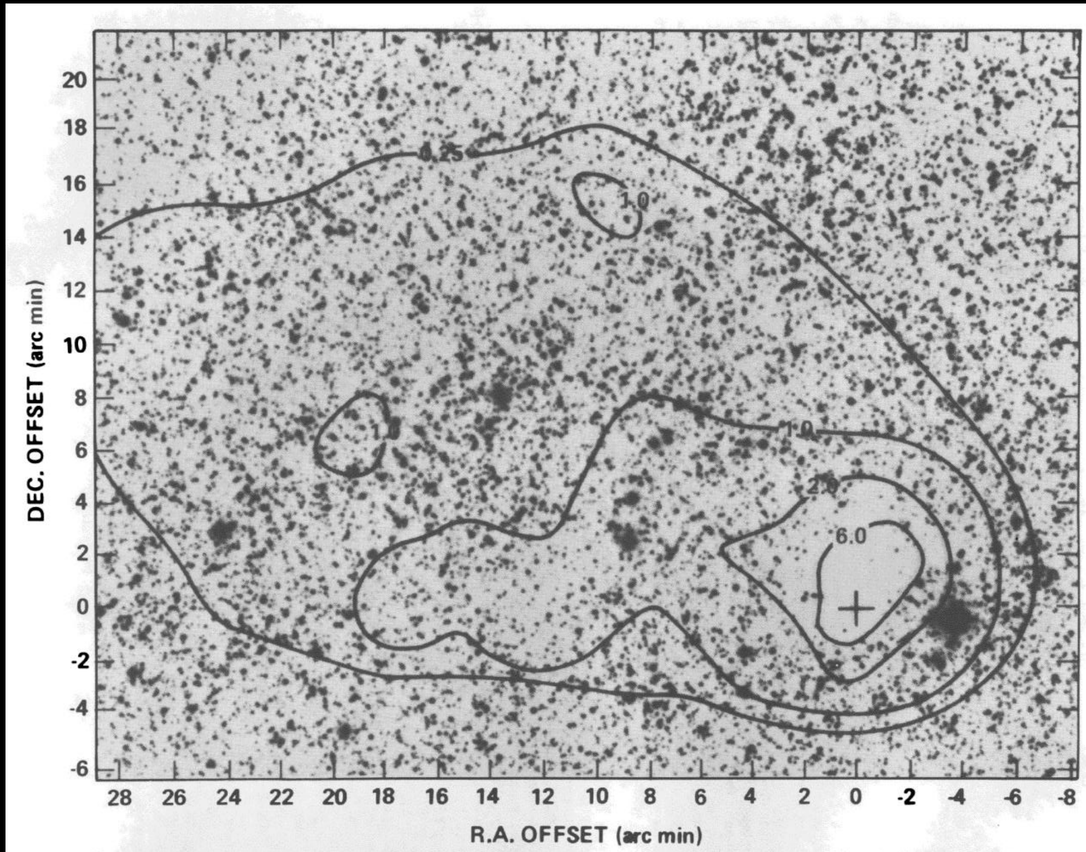
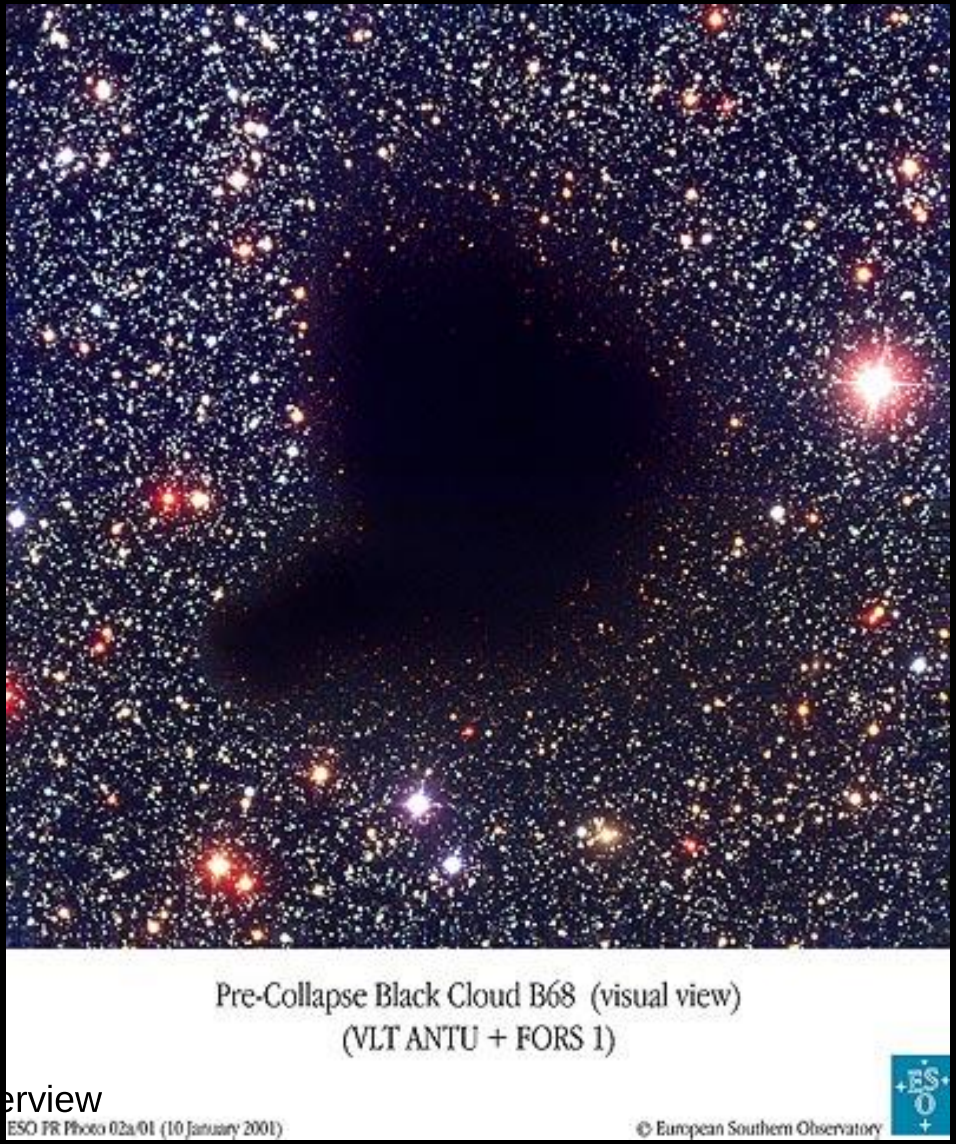


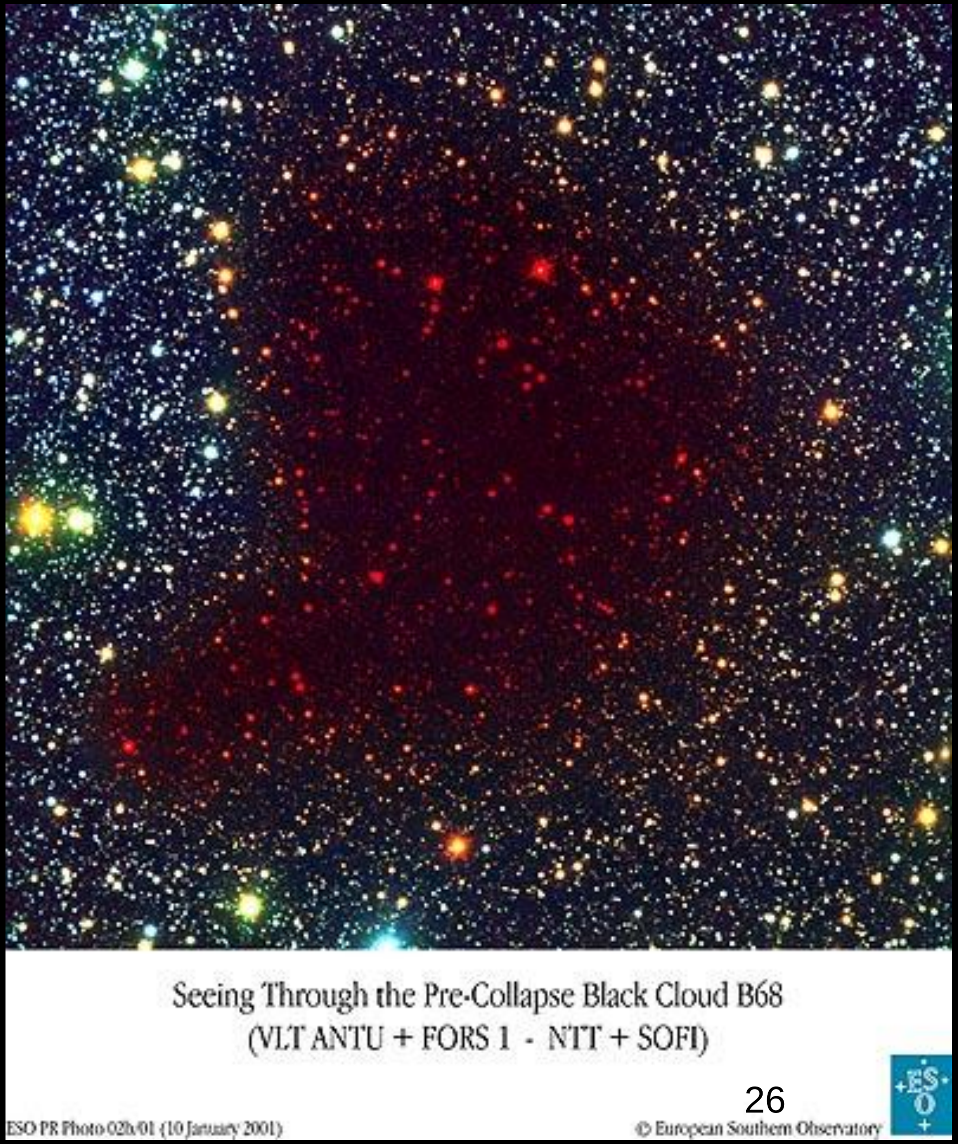
FIG. 1.—The optical image of B335 on the blue POSS print. Superposed on it are the $N(H_2)$ contours in units of 10^{21} cm^{-2}; the derivation of $N(H_2)$ is discussed in § IIIa(i). In the SW corner there is a highly obscured core region ~2′ × 3′ surrounded by an extended envelope covering ~34′ × 20′.

Frerking et al. (1987)

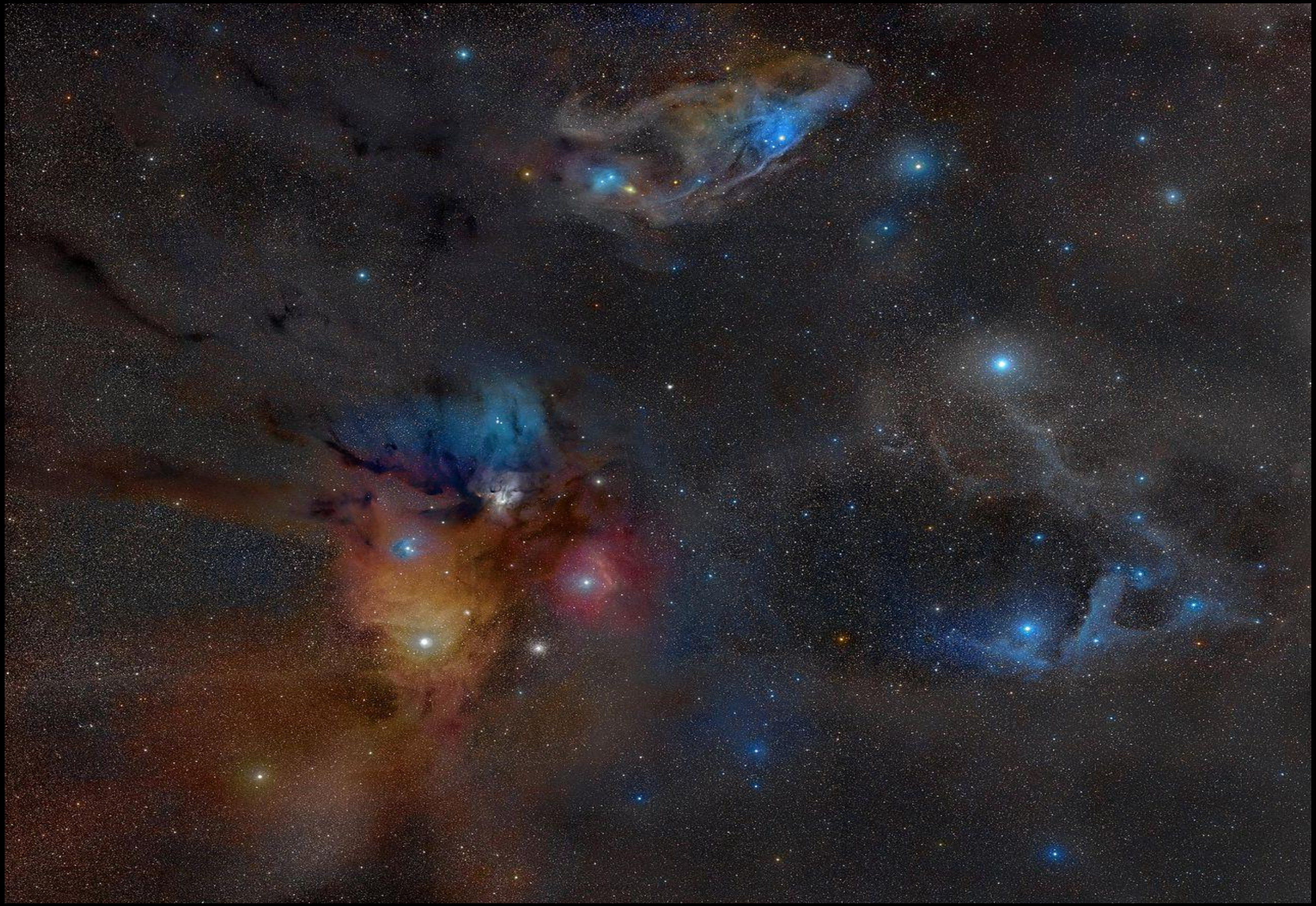
Optical Composite

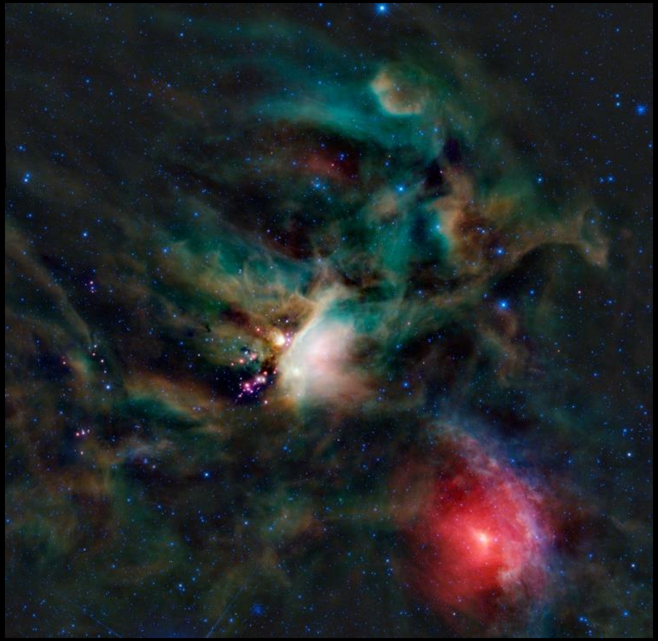
Optical/IR composite





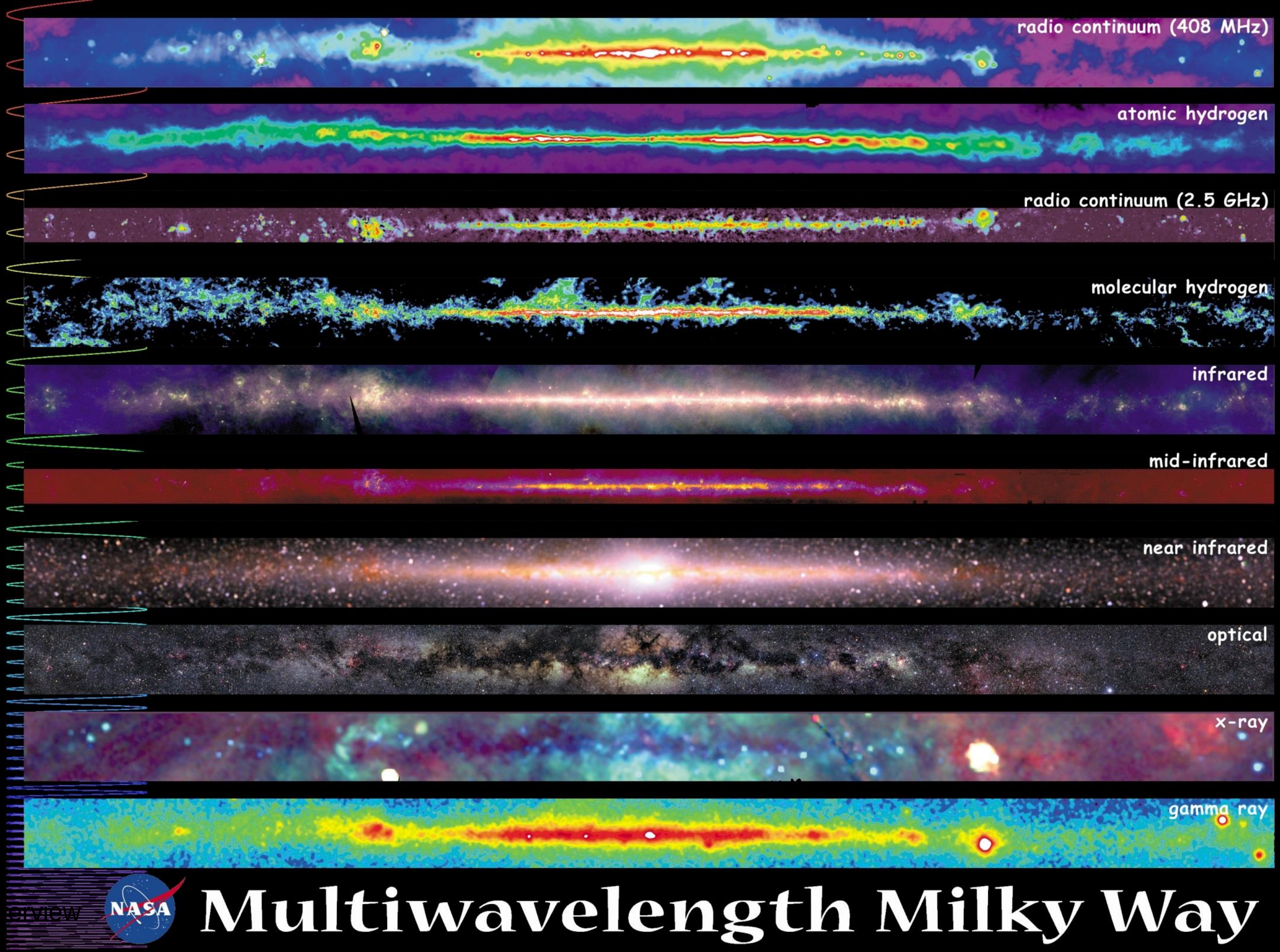
ρ Ophiuchi cloud complex





WISE

https://en.wikipedia.org/wiki/Rho_Ophiuchi#/media/File:Rho_Ophiucus_Widefield.jpg



http://adc.gsfc.nasa.gov/mw

Multiwavelength Milky Way

Interstellar Medium (ISM)

- ISM is very sparse --- gas and dust (solid); no liquid *(why?)*

  [star-star distance] / [stellar diameter]
  $\sim 1\ \mathrm{pc}/10^{11}\ \mathrm{cm} \sim 3 \times 10^{7}: 1$; in terms of volume (space) $\sim 10^{22}$

  (What about galaxies?)

  ➔ Stars truly tiny compared to space in between

- Mass: [gas + dust] / total ~ 15%, but density very low
  (What is the number density of air in this room?)

- Gas, dust, radiation, magnetic fields, cosmic rays (i.e., charged particles)
- ISM mass = 15% of the total visible matter of the MW galaxy
- ISM: 99% mass in gas, 1% in dust
- Of the gas: 90%, H; 10% He
- Hydrogen: mainly H I (atomic), H II (ionized), and H_2 (molecular)
- Studies of ISM ---
  - Beginning of evolution of baryonic matter “recombination”
  - Stars form out of ISM
  - Important ingredient of a galaxy

Material Constituents of the ISM

Name	T (K)	n (cm^{-3})	Properties
Hot, intercloud and "coronal" gas	10^6	10^{-4}	
Warm intercloud gas	10^4	10^{-1}	
Diffuse cloud (H I)	10^2	$10^{-1} - 1$	Mostly H I; $n_e/n_0 \approx 10^{-4}$
H II regions	10^4	>10	
Dark Molecular Clouds	10	$> 10^3$	Mostly H_2 and dust
Supernova Remnants	$10^4 \sim 10^7$	>1	
Planetary Nebulae			

Energy Density in the Local ISM

Component	u (eV/cm^{-3})	Properties
Cosmic microwave background	0.265	$T_{\rm CMB} = 2.725$ K
FIR radiation from dust	0.31	
Starlight	0.54	$h\nu < 13.6$ eV
Thermal kinetic energy	0.49	
Turbulent kinetic energy	0.22	$\langle n_H \rangle = 1$ cm^{-3}
Magnetic field	0.89	$B^2/8\pi; \langle B \rangle = \mu$G
Cosmic rays	1.39	

There seems to be equipartition between these energies. Why?

Read Draine's book, page 10

Draine

THE ASTROPHYSICAL JOURNAL, **218**: 148–169, 1977 November 15

A THEORY OF THE INTERSTELLAR MEDIUM: THREE COMPONENTS REGULATED BY SUPERNOVA EXPLOSIONS IN AN INHOMOGENEOUS SUBSTRATE

CHRISTOPHER F. MCKEE
Departments of Physics and Astronomy, University of California, Berkeley

AND

JEREMIAH P. OSTRIKER
Princeton University Observatory
Received 1977 February 3; accepted 1977 May 2

ABSTRACT

Supernova explosions in a cloudy interstellar medium produce a three-component medium in which a large fraction of the volume is filled with hot, tenuous gas. In the disk of the galaxy the evolution of supernova remnants is altered by evaporation of cool clouds embedded in the hot medium. Radiative losses are enhanced by the resulting increase in density and by radiation from the conductive interfaces between clouds and hot gas. Mass balance (cloud evaporation rate = dense shell formation rate) and energy balance (supernova shock input = radiation loss) determine the density and temperature of the hot medium with $(n, T) = (10^{-2.5}, 10^{5.7})$ being representative values. Very small clouds will be rapidly evaporated or swept up. The outer edges of "standard" clouds ionized by the diffuse UV and soft X-ray backgrounds provide the warm ($\sim 10^4$ K) ionized and neutral components. A self-consistent model of the interstellar medium developed herein accounts for the observed pressure of interstellar clouds, the galactic soft X-ray background, the O VI absorption line observations, the ionization and heating of much of the interstellar medium, and the motions of the clouds. In the halo of the galaxy, where the clouds are relatively unimportant, we estimate $(n, T) = (10^{-3.3}, 10^{6.0})$ below one pressure scale height. Energy input from halo supernovae is probably adequate to drive a galactic wind.

Zooming out from Fig. 1

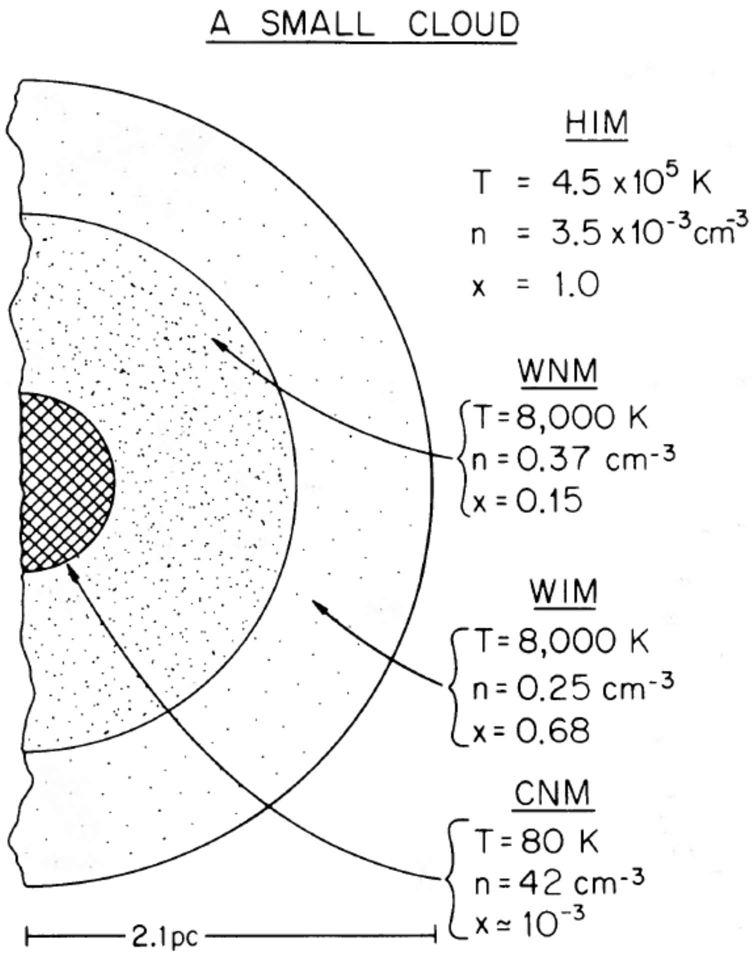


FIG. 1

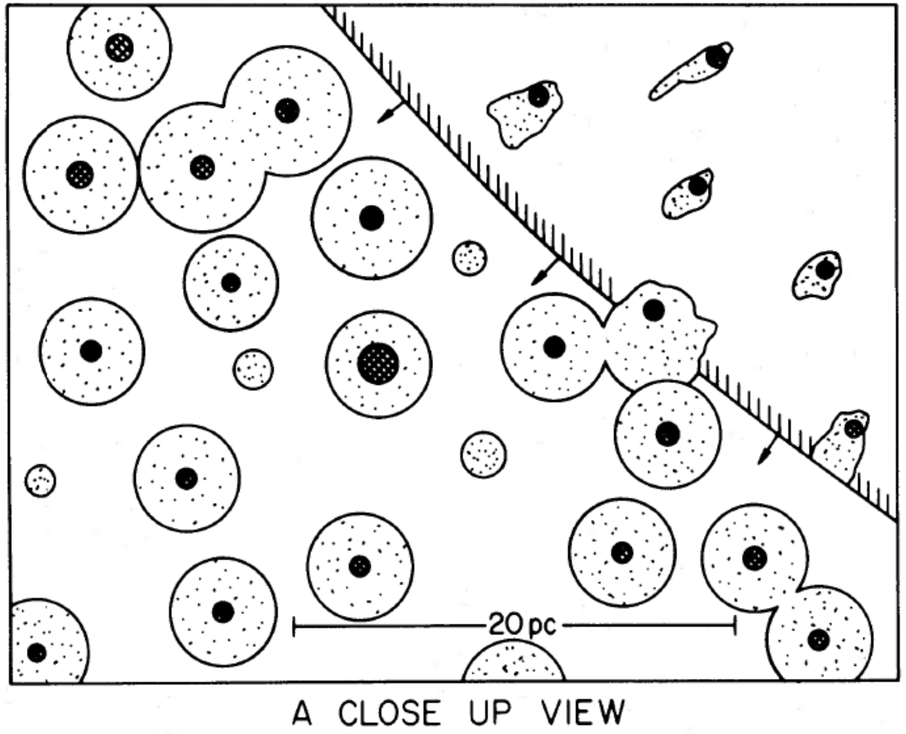


FIG. 2

FIG. 1.—Cross section of a characteristic small cloud. The crosshatched region shows the cold core, which gives the usual optical absorption lines. Next is the warm neutral medium (WNM) with ionization produced by soft X-ray background. The outer layer (WIM) is gas largely ionized by stellar UV background. Typical values of hydrogen density n, temperature T, and ionization $x = n_e/n$ are shown for each component, except that a higher than average value of the soft X-ray flux has been assumed in order to produce a significant amount of WNM at this pressure.

FIG. 2.—Small-scale structure of the interstellar medium. A cross section of a representative region 30 pc × 40 pc in extent is shown, with the area of the features being approximately proportional to their filling factors. A supernova blast wave is expanding into the region from the upper right. The radius of the neutral cores of the clouds (represented by crosshatching) ranges from about 0.4 to 1 pc in this small region; all the clouds with cores have warm envelopes (*dotted regions*) of radius $a_w \sim 2.1$ pc. A few clouds are too small to have cores. The envelopes of clouds inside the SNR are compressed and distorted.

Zooming further out from Fig. 2

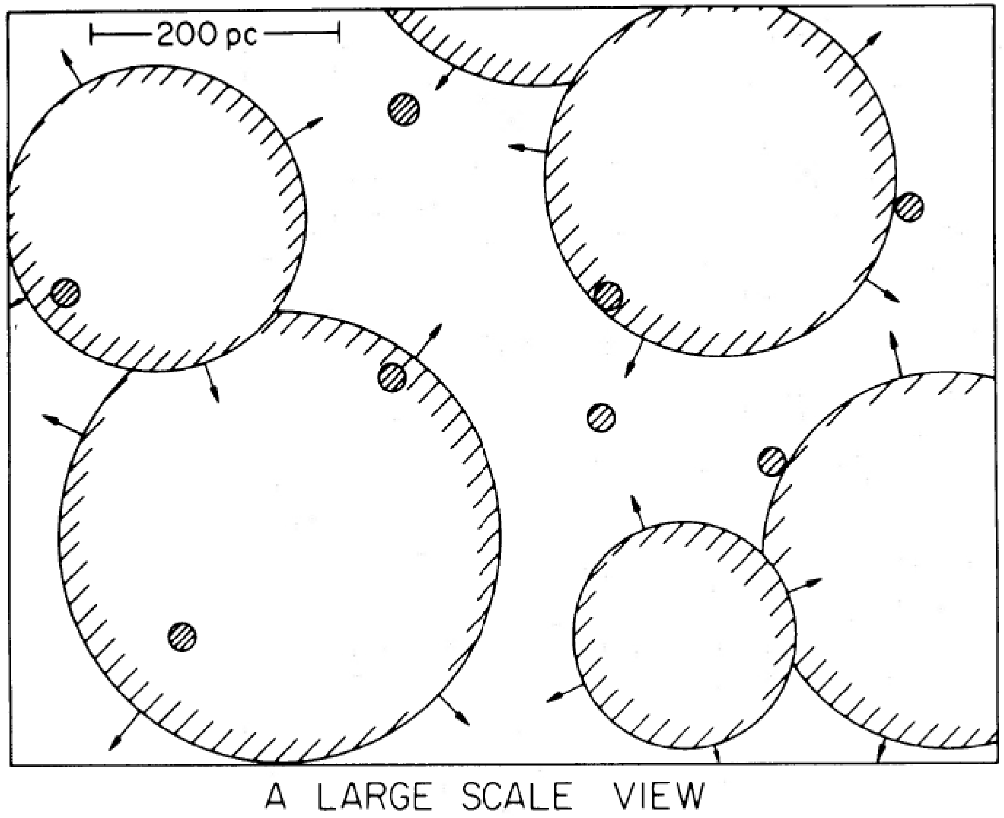


FIG. 3.—Large-scale structure of the interstellar medium. The scale here is 20 times greater than in Fig. 1: the region is 600 × 800 pc. Only SNRs with $R < R_c = 180$ pc and clouds with $a_0 > 7$ pc are shown. Altogether about 9000 clouds, most with $a_w \sim 2.1$ pc, would occur in a region this size.

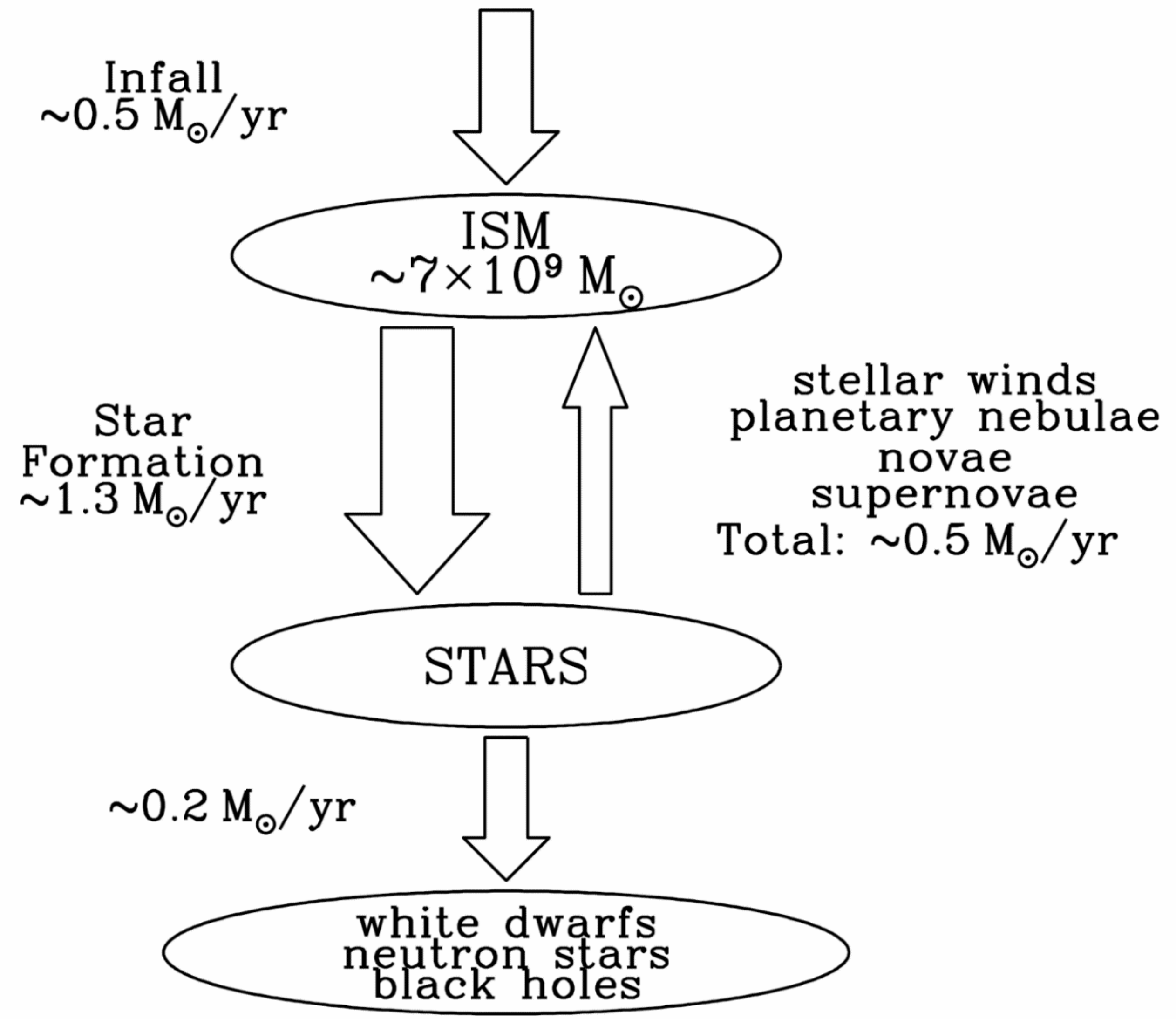
Exercise

What is the gas number density n for the Sun as a whole (average)? At the center?

(*How are these known?*)

What is the gas pressure in a typical interstellar diffuse cloud? In a molecular cloud? How do these compare to the "vacuum" on Earth?

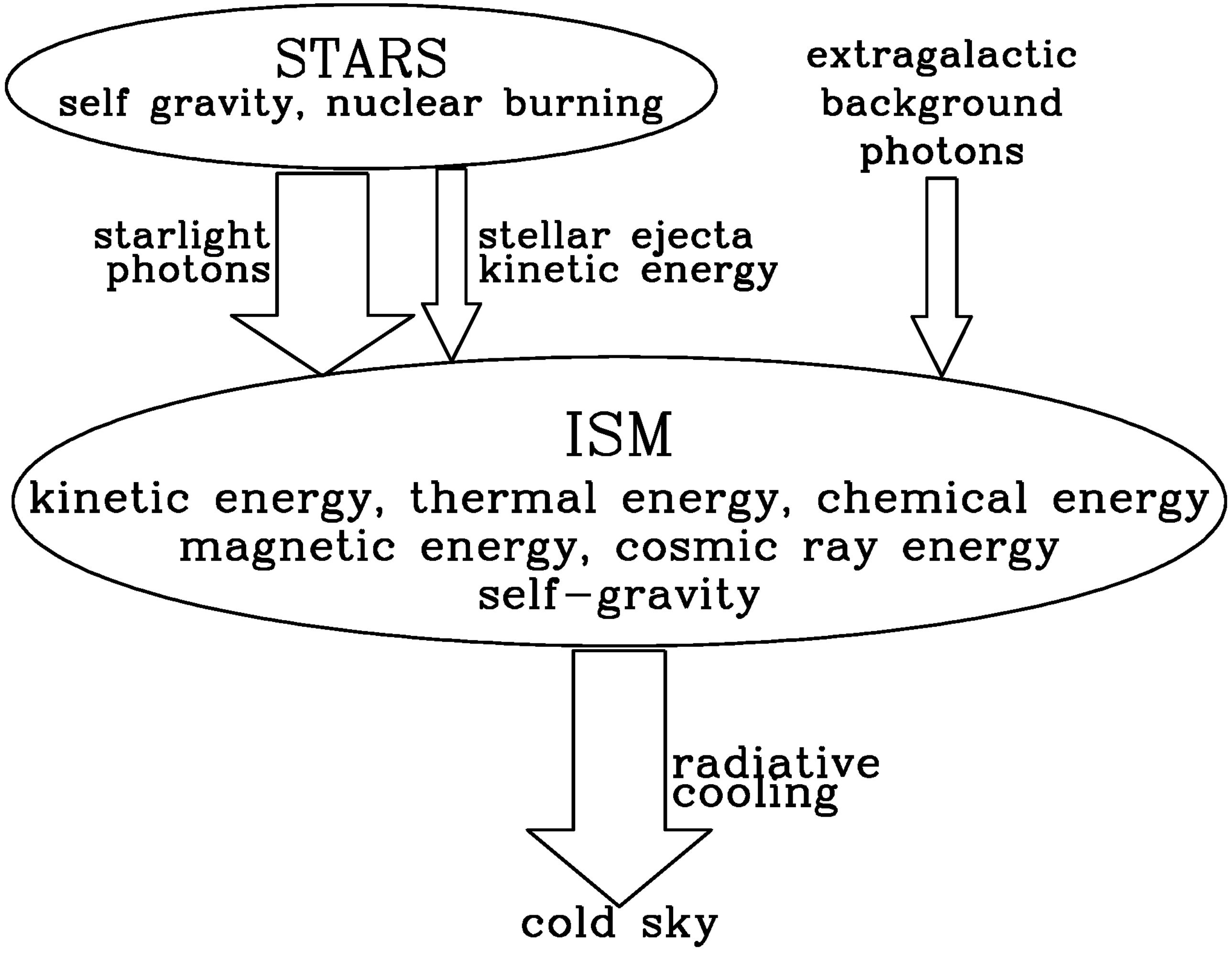
In this course, we will discuss mainly the diffuse clouds, in ionized, atomic and molecular forms, whereas the warm and hot intercloud gas will be reviewed only briefly.



Draine

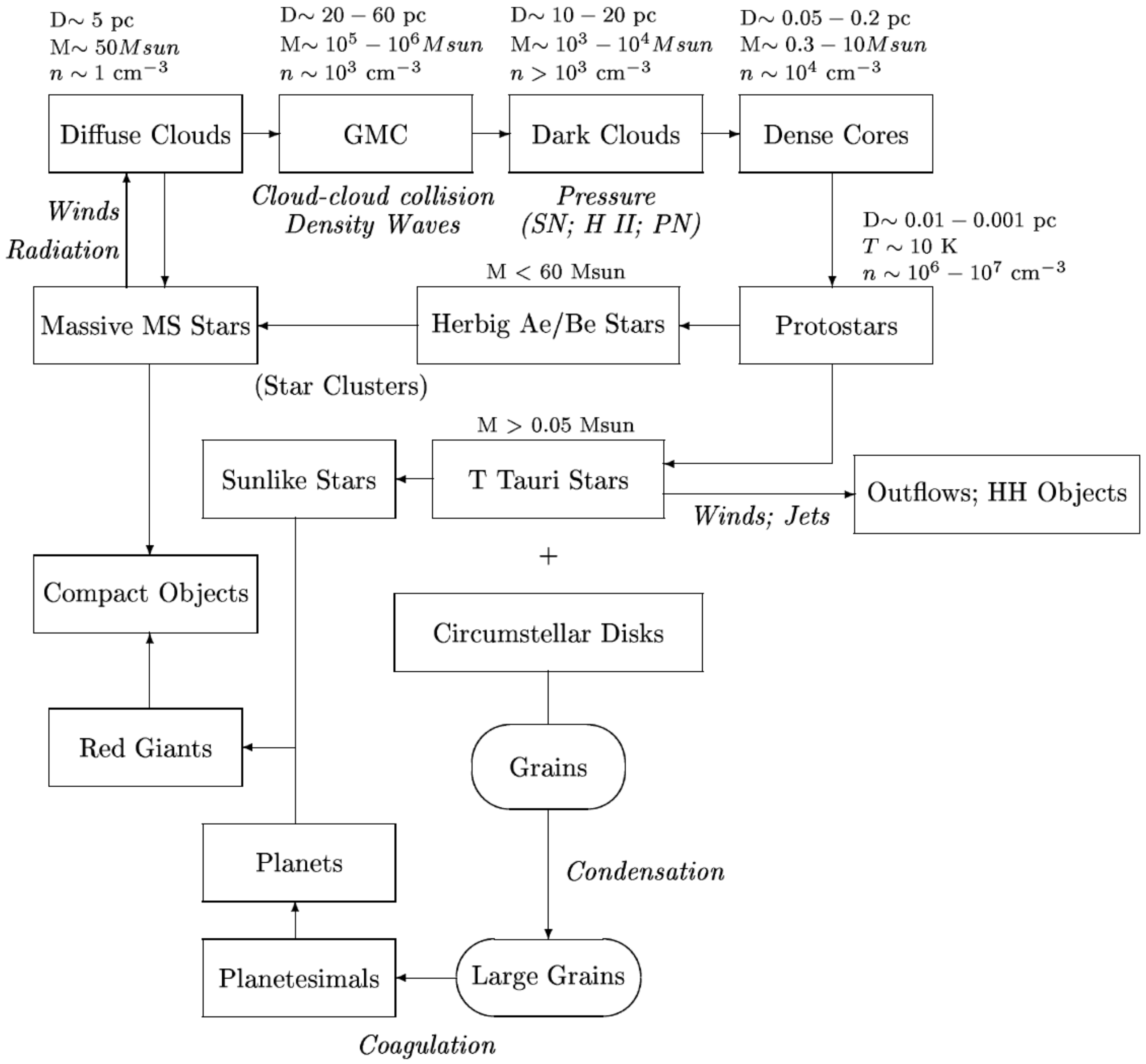
Flow of baryons in the Milky Way

The ISM is far from thermodynamic equilibrium.

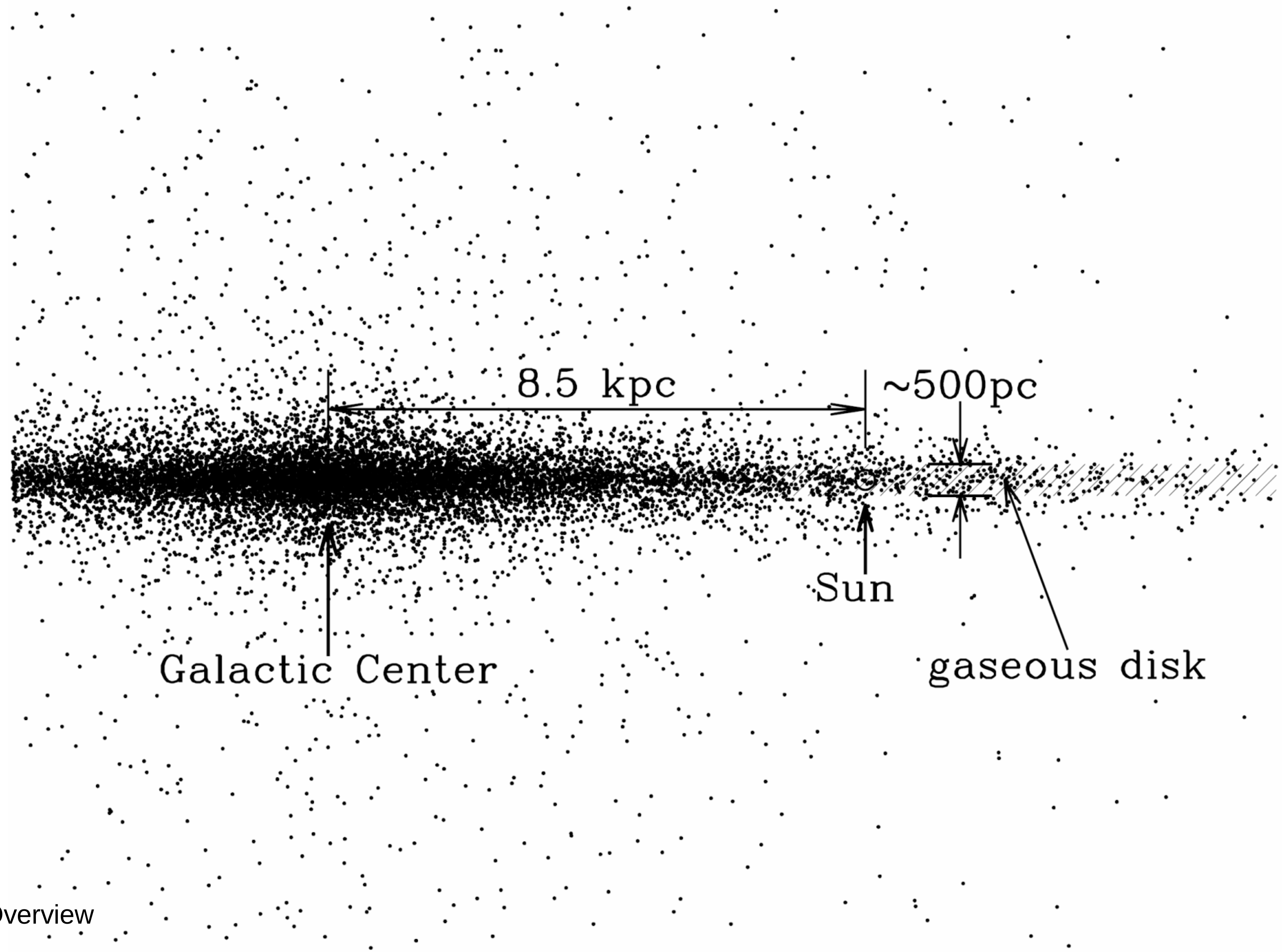


Draine

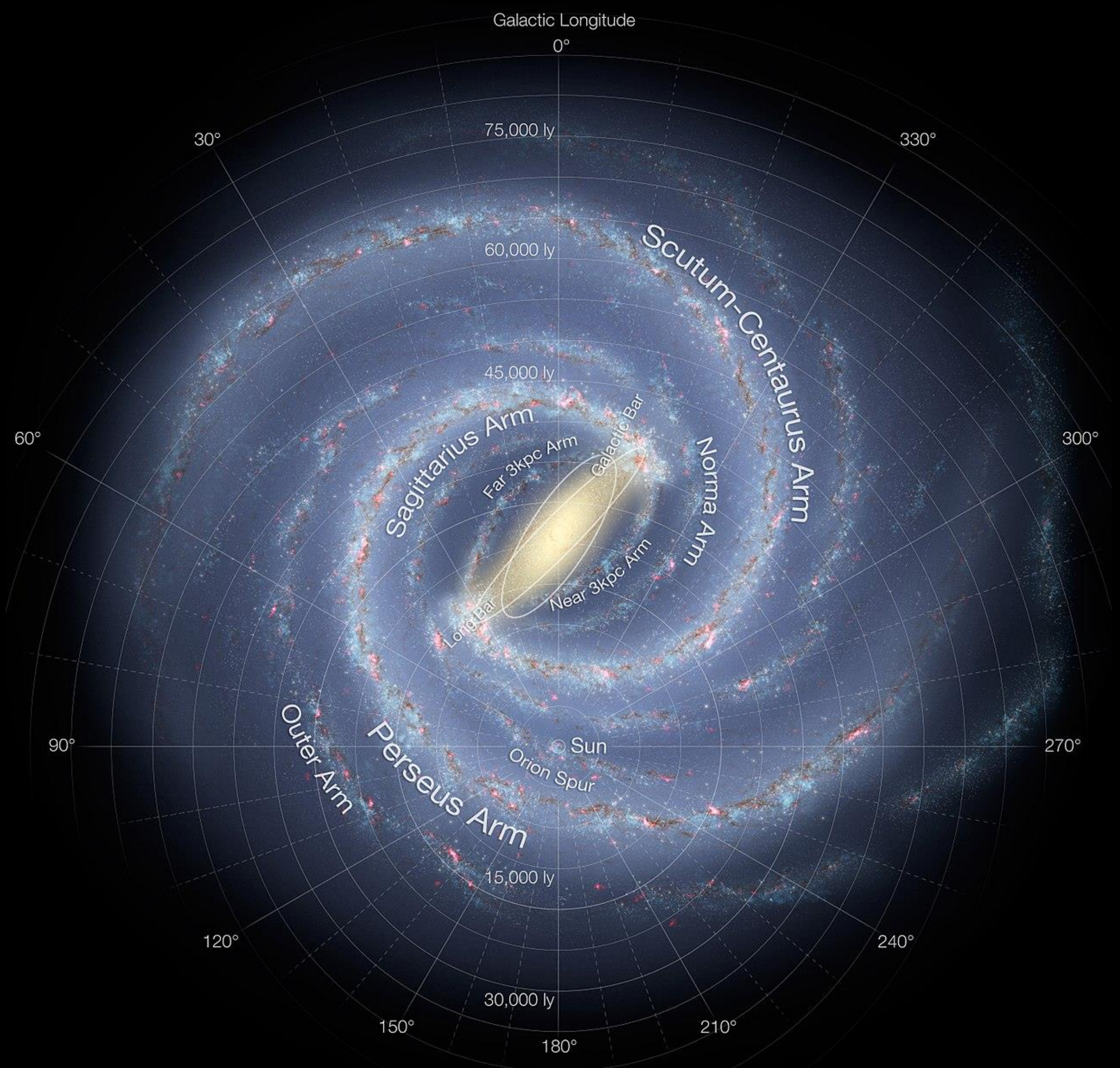
Flow of energy in the Milky Way



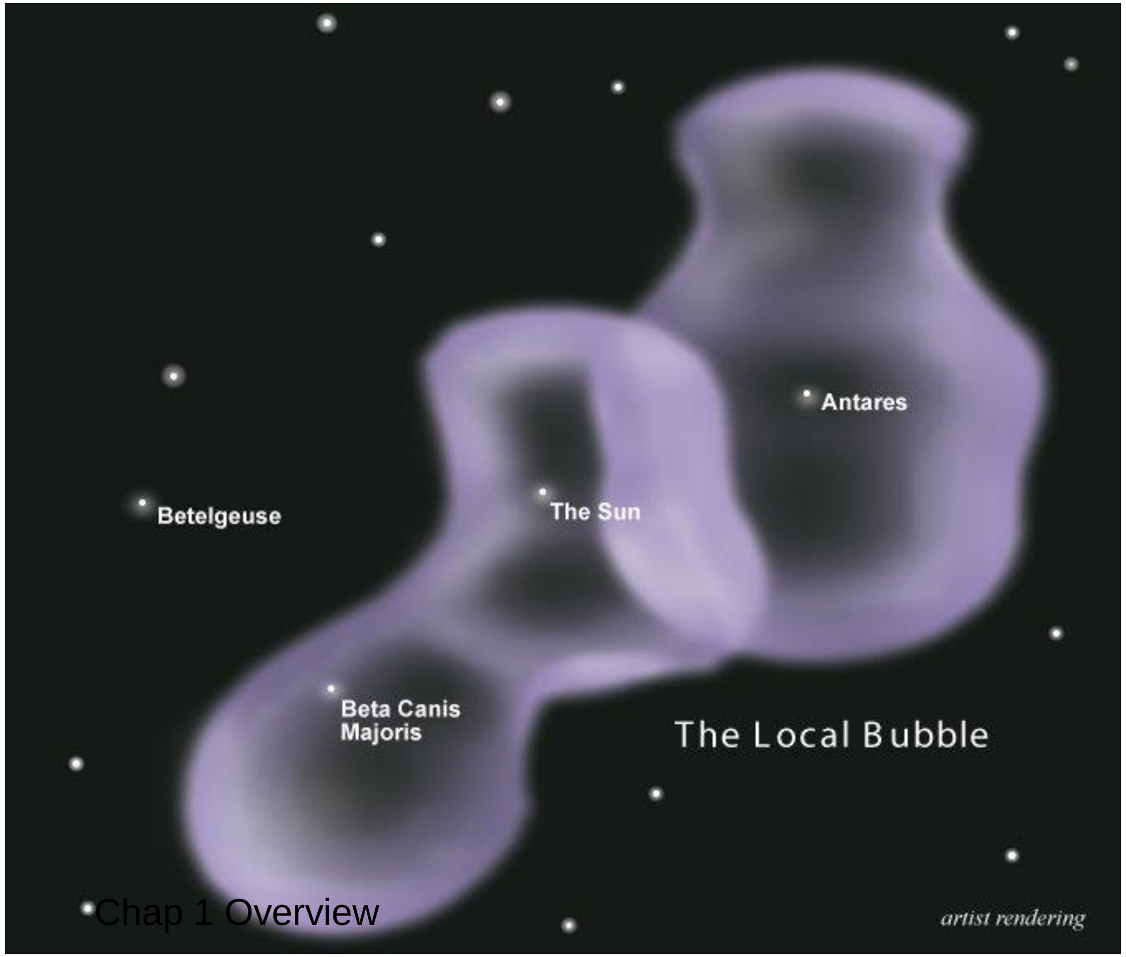
Galactic Ecology



Draine

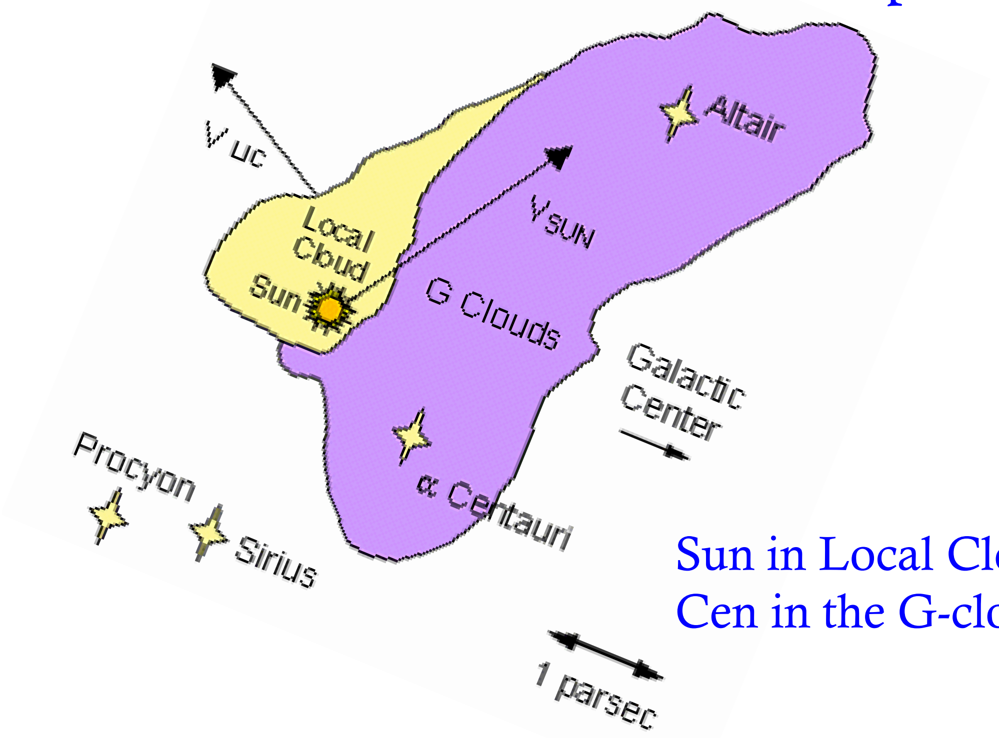

Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur

The Local Bubble A cavity of sparse, hot gas in the Orion Arm; ~100 pc across; $n \sim 0.05\ \mathrm{cm}^{-3} \sim 0.1$ of ISM; likely by SN explosions 10--30 Myr ago?



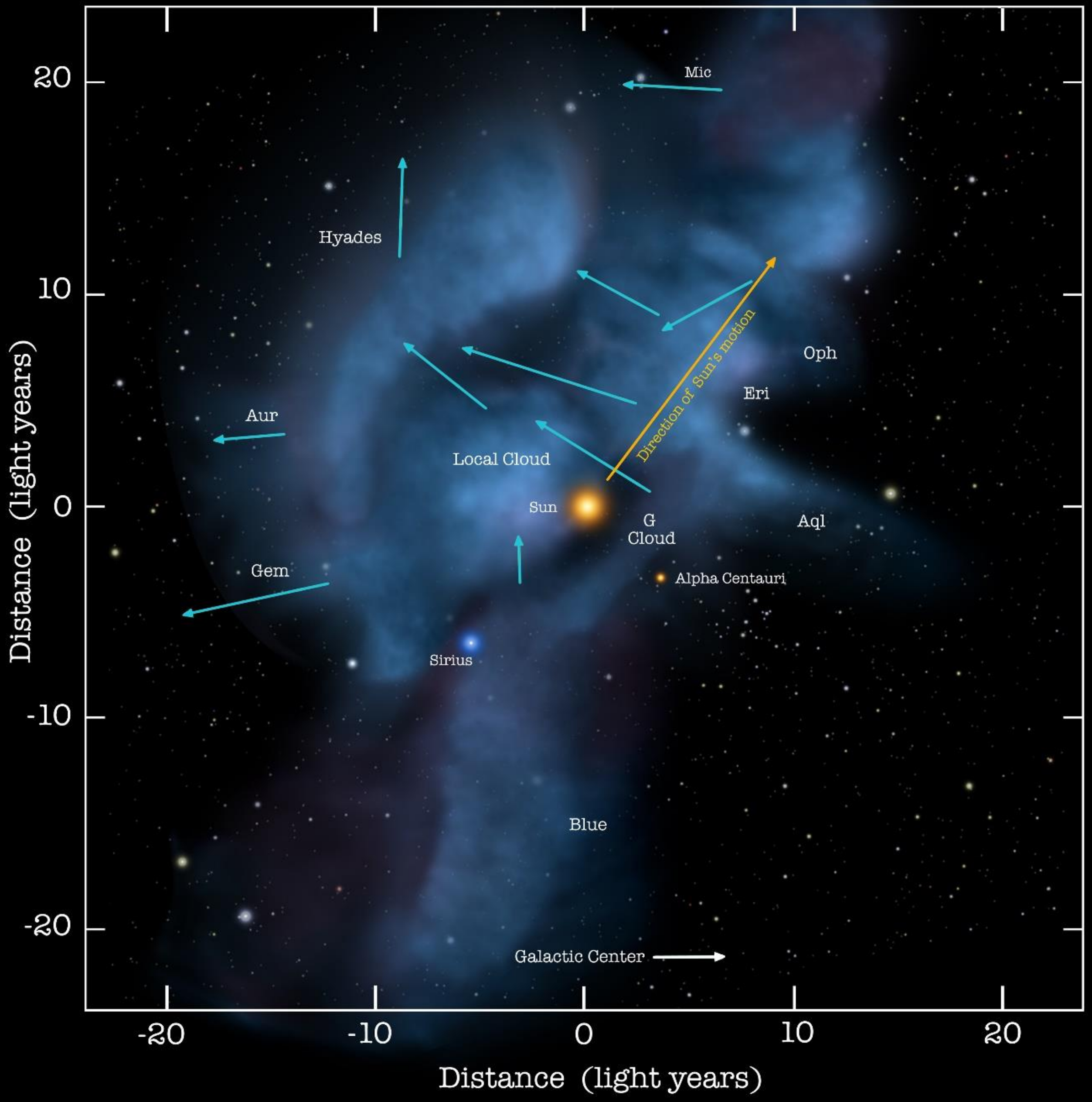
Where is the supernova (remnant)?

Check out the Orion-Eridanus Superbubble



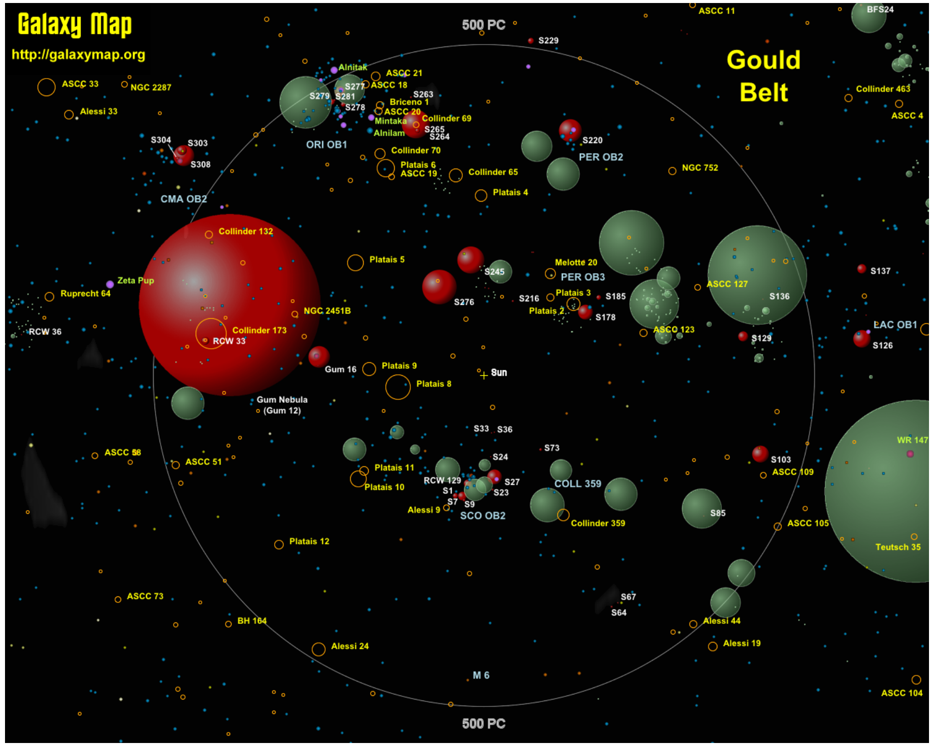
Sun in Local Cloud; Alpha Cen in the G-cloud complex

https://en.wikipedia.org/wiki/Local_Bubble https://en.wikipedia.org/wiki/Local_Interstellar_Cloud

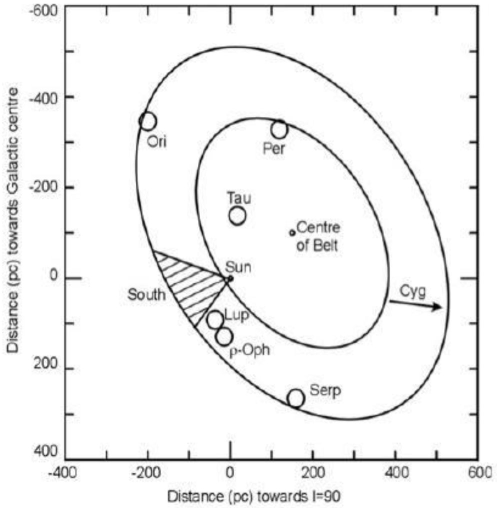


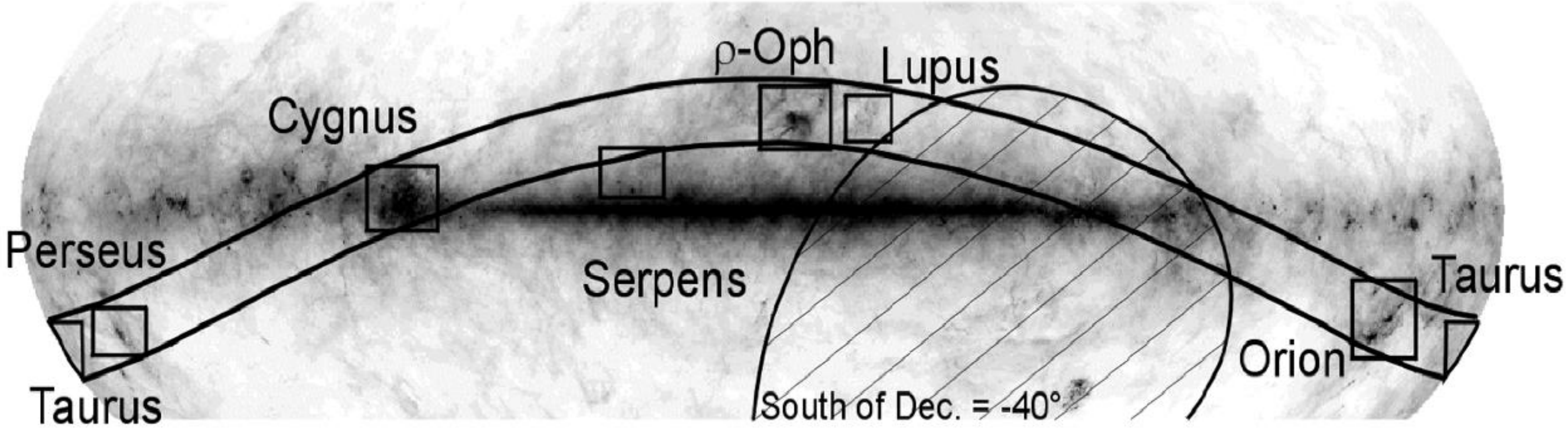
The **Gould Belt**, a (partial) ring in the sky, ~1 kpc across, centered on a point 100 pc from the Sun and tilted about 20 deg to the Galactic plane, containing star-forming molecular clouds and OB stars = local spiral arm

Origin unknown (dark matter induced star formation?)



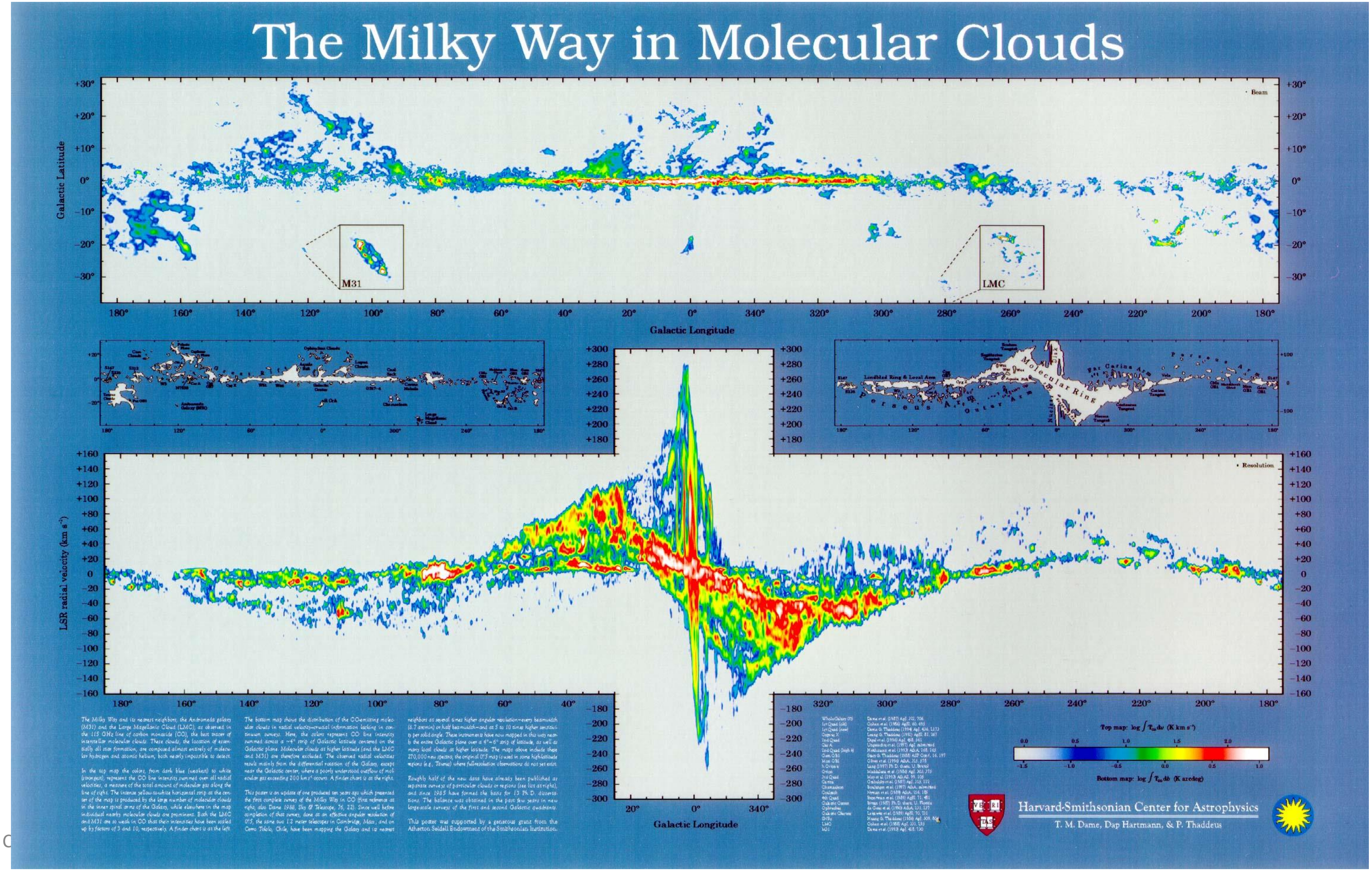
http://galaxymap.org/detail_maps/download_maps/gould.png





Gould's Belt superimposed on to an IRAS 100 micron emission map

http://www.jach.hawaii.edu/JCMT/surveys/gb/

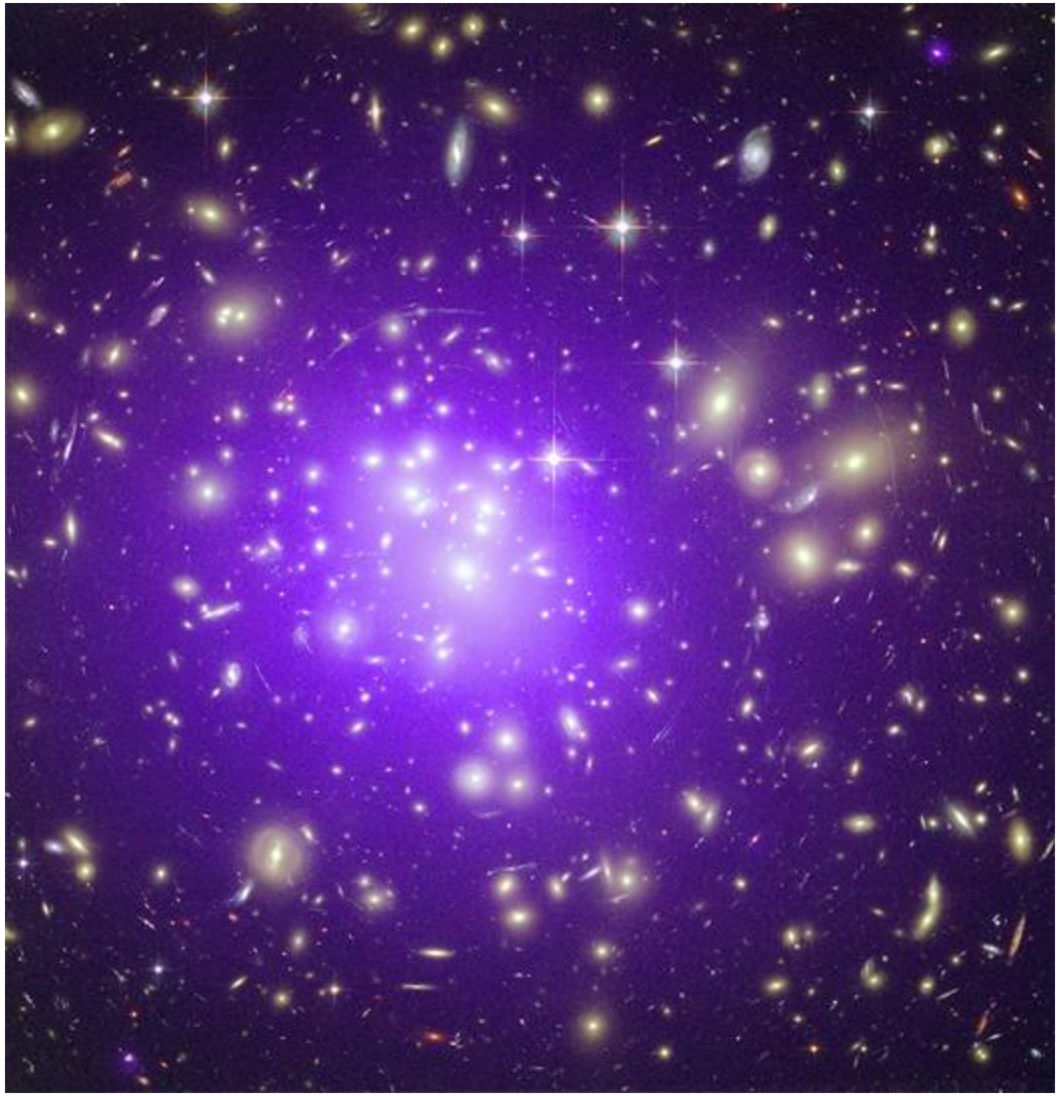

The Milky Way in Molecular Clouds
Galactic Latitude
Galactic Longitude
Beam
M31
LMC
LSR radial velocity (km s-1)
Resolution
Molecular Ring
Perseus Arm
Far Carina Arm
Outer Arm
Harvard-Smithsonian Center for Astrophysics
T. M. Dame, Dap Hartmann, & P. Thaddeus

Intergalactic medium

Warm to hot (10^5 to 10^7 K)
sparse ($1/m^3$)

Intracluster medium

Hot (10^7 to 10^8 K)
sparse ($1000/m^3$)



Chandra image (100 MK) of Abell1689