

# Interstellar Medium

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

# Interstellar Medium --- Syllabus

NCUIA 2025 Spring

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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	<b>04/10</b>	<b>Midterm Exam</b>

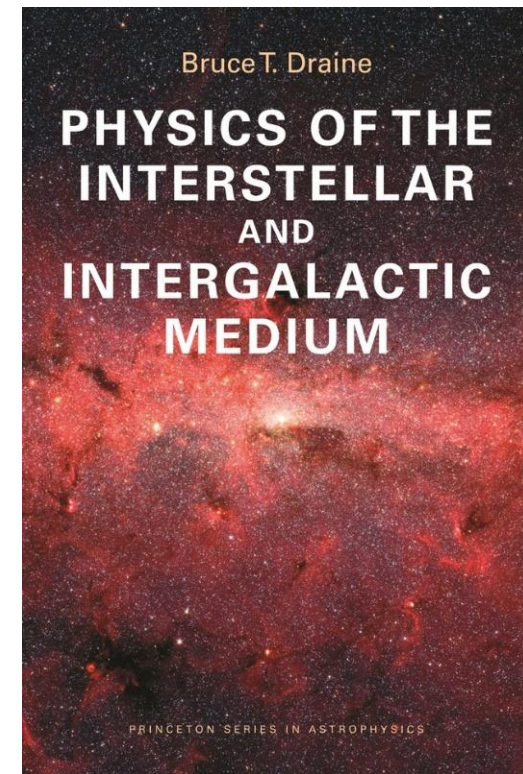
#	Date	
09	04/17	30 min extra
10	04/24	No class*; Mexico
11	05/01	30 min extra
12	05/08	30 min extra
13	05/15	
14	05/22	
15	05/29	
16	<b>06/06</b>	<b>Final Exam</b>

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  $1\text{\AA}$ , 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.



<i>Contents</i>	
Preface	xvii
1. Introduction	1
1.1 Organization of the ISM: Characteristic Phases	4
1.2 Elemental Composition	9
1.3 Energy Densities	9
2. Collisional Processes	11
2.1 Collisional Rate Coefficients	11
2.2 Inverse-Square Law Forces: Elastic Scattering	12
2.3 Electron–Ion Inelastic Scattering: Collision Strength $\Omega_{u\ell}$	17
2.4 Ion–Neutral Collision Rates	17
2.5 Electron–Neutral Collision Rates	20
2.6 Neutral–Neutral Collision Rates	21
3. Statistical Mechanics and Thermodynamic Equilibrium	22
3.1 Partition Functions	22
3.2 Detailed Balance: The Law of Mass Action	23
3.3 Ionization and Recombination	24
3.4 Saha Equation	25
3.5 Detailed Balance: Ratios of Rate Coefficients	26
3.6 Detailed Balance: Ratios of Cross Sections	26
3.7 Example: Three-Body Recombination	28
3.8 Departure Coefficients	30
4. Energy Levels of Atoms and Ions	32
4.1 Single-Electron Orbitals	32
4.2 Configurations	32
4.3 Spectroscopic Terms	33
4.4 Fine Structure: Spin-Orbit Interaction	34
4.5 Designation of Energy Levels for Atoms and Ions: Spectroscopic Notation	34
4.6 Hyperfine Structure: Interaction with Nuclear Spin	36

viii		CONTENTS	
4.7	Zeeman Effect		37
4.8	Further Reading		37
5.	Energy Levels of Molecules		38
5.1	Diatomic Molecules		38
5.2	★ Energy Levels of Nonlinear Molecules		47
5.3	★ Zeeman Splitting		51
5.4	Further Reading		52
6.	Spontaneous Emission, Stimulated Emission, and Absorption		53
6.1	Emission and Absorption of Photons		53
6.2	Absorption Cross Section		55
6.3	Oscillator Strength		56
6.4	Intrinsic Line Profile		57
6.5	Doppler Broadening: The Voigt Line Profile		58
6.6	Transition from Doppler Core to Damping Wings		59
6.7	Selection Rules for Radiative Transitions		60
7.	Radiative Transfer		63
7.1	Physical Quantities		63
7.2	Equation of Radiative Transfer		65
7.3	Emission and Absorption Coefficients		66
7.4	Integration of the Equation of Radiative Transfer		66
7.5	Maser Lines		68
8.	HI 21-cm Emission and Absorption		70
8.1	HI Emissivity and Absorption Coefficient		70
8.2	Optically Thin Cloud		72
8.3	Spin Temperature Determination Using Background Radio Sources		73
9.	Absorption Lines: The Curve of Growth		75
9.1	Absorption Lines		75
9.2	Optically Thin Absorption, $\tau_0 \lesssim 1$		77
9.3	Flat Portion of the Curve of Growth, $10 \lesssim \tau_0 \lesssim \tau_{\text{damp}}$		77
9.4	Damped Portion of the Curve of Growth, $\tau_0 \gtrsim \tau_{\text{damp}}$		79
9.5	Approximation Formulae for $W$		81
9.6	Doublet Ratio		81
9.7	Lyman Series of Hydrogen: $\text{Ly } \alpha$ , $\text{Ly } \beta$ , $\text{Ly } \gamma$ , . . .		83
9.8	Lyman Limit		84
9.9	H <sub>2</sub> : Lyman and Werner Bands		85
9.10	“Metal” Lines		86
9.11	Abundances in HI Gas		90

CONTENTS		ix	
10.	Emission and Absorption by a Thermal Plasma		92
10.1	Free–Free Emission (Bremsstrahlung)		92
10.2	★ Gaunt Factor		93
10.3	Frequency-Averaged Gaunt Factor		95
10.4	Free–Free Absorption		95
10.5	Emission Measure		96
10.6	Free–Bound Transitions: Recombination Continuum		97
10.7	Radio Recombination Lines		97
11.	Propagation of Radio Waves through the ISM		101
11.1	Dispersion Relation for Cold Plasmas		101
11.2	Dispersion		102
11.3	Faraday Rotation		105
11.4	★ Refraction		109
11.5	★ Scintillation		111
11.6	★ Interstellar Electron Density Power Spectrum		113
11.7	★ Extreme Scattering Events		116
12.	Interstellar Radiation Fields		119
12.1	Galactic Synchrotron Radiation		119
12.2	Cosmic Microwave Background Radiation		120
12.3	Free–Free Emission and Recombination Continuum		121
12.4	Infrared Emission from Dust		121
12.5	Starlight in an HI Region		123
12.6	X Rays from Hot Plasma		125
12.7	Radiation Field in a Photodissociation Region near a Hot Star		125
13.	Ionization Processes		127
13.1	Photoionization		128
13.2	Auger Ionization and X-Ray Fluorescence		131
13.3	Secondary Ionizations		132
13.4	Collisional Ionization		134
13.5	Cosmic Ray Ionization		134
14.	Recombination of Ions with Electrons		137
14.1	Radiative Recombination		137
14.2	Radiative Recombination of Hydrogen		138
14.3	★ Radiative Recombination: Helium		146
14.4	Radiative Recombination: Heavy Elements		150
14.5	Dielectronic Recombination		151
14.6	Dissociative Recombination		153
14.7	Charge Exchange		154

X	CONTENTS
14.8	Ion Neutralization by Dust Grains 157
14.9	Ionization Balance in Collisionally Ionized Gas 159
15.	Photoionized Gas 162
15.1	H II Regions as Strömgren Spheres 162
15.2	Time Scales 165
15.3	Neutral Fraction within an H II Region 166
15.4	Dusty H II Regions with Radiation Pressure 167
15.5	Ionization of Helium and Other Elements 172
15.6	Planetary Nebulae 175
15.7	★ Escape of Lyman $\alpha$ 176
15.8	★ Ionization by Power-Law Spectra 180
16.	Ionization in Predominantly Neutral Regions 182
16.1	HI Regions: Ionization of Metals 182
16.2	Cool HI Regions: Ionization of Hydrogen 184
16.3	Warm HI Regions 185
16.4	Diffuse Molecular Gas 186
16.5	Dense Molecular Gas: Dark Clouds 188
17.	Collisional Excitation 190
17.1	Two-Level Atom 190
17.2	Critical Density $n_{\text{crit},u}$ 191
17.3	Example: HI Spin Temperature 192
17.4	Example: C II Fine Structure Excitation 195
17.5	★ Three-Level Atom 197
17.6	★ Example: Fine Structure Excitation of C I and O I 198
17.7	★ Measurement of Density and Pressure Using C I 198
18.	Nebular Diagnostics 203
18.1	Temperature Diagnostics: Collisionally Excited Optical/UV Lines 204
18.2	Density Diagnostics: Collisionally Excited Optical/UV Lines 209
18.3	Density Diagnostics: Fine-Structure Emission Lines 210
18.4	★ Other Diagnostic Methods 212
18.5	Abundance Determination from Collisionally Excited Lines 214
18.6	★ Abundances from Optical Recombination Lines 215
18.7	★ Ionization/Excitation Diagnostics: The BPT Diagram 215
19.	Radiative Trapping 219
19.1	Escape Probability Approximation 219
19.2	Homogeneous Static Spherical Cloud 221
19.3	Example: CO $J = 1-0$ 222

CONTENTS	xi
19.4	★ LVG Approximation: Hubble Flow 224
19.5	Escape Probability for Turbulent Clouds 225
19.6	CO 1–0 Emission as a Tracer of H <sub>2</sub> Mass: CO “X-Factor” 227
20.	Optical Pumping 229
20.1	UV Pumping by Continuum 229
20.2	★ Infrared Pumping: OH 231
20.3	★ UV Pumping by Line Coincidence: Bowen Fluorescence 232
21.	Interstellar Dust: Observed Properties 235
21.1	Interstellar Extinction 236
21.2	Parametric Fits to the Extinction Curve 239
21.3	Polarization by Interstellar Dust 240
21.4	Scattering of Starlight by Interstellar Dust 242
21.5	Size Distribution of Interstellar Dust 243
21.6	★ Purcell Limit: Lower Limit on Dust Volume 243
21.7	Infrared Emission 246
21.8	★ Luminescence 247
22.	Scattering and Absorption by Small Particles 248
22.1	Cross Sections and Efficiency Factors 248
22.2	Dielectric Function and Refractive Index 249
22.3	Electric Dipole Limit: Size $\ll \lambda$ 251
22.4	Limiting Behavior at Long Wavelengths 252
22.5	Sizes Comparable to Wavelength: Mie Theory 253
22.6	★ Nonspherical Particles 256
22.7	Interstellar Grains 258
23.	Composition of Interstellar Dust 263
23.1	Abundance Constraints 263
23.2	Presolar Grains in Meteorites 266
23.3	Observed Spectral Features of Dust 267
23.4	Silicates 271
23.5	Polycyclic Aromatic Hydrocarbons 274
23.6	★ Graphite 277
23.7	★ Diamond 278
23.8	★ Amorphous Carbons, Including Hydrogenated Amorphous Carbon 278
23.9	★ Fullerenes 278
23.10	Models for Interstellar Dust 279
24.	Temperatures of Interstellar Grains 285
24.1	Heating and Cooling of “Classical” Dust Grains 285

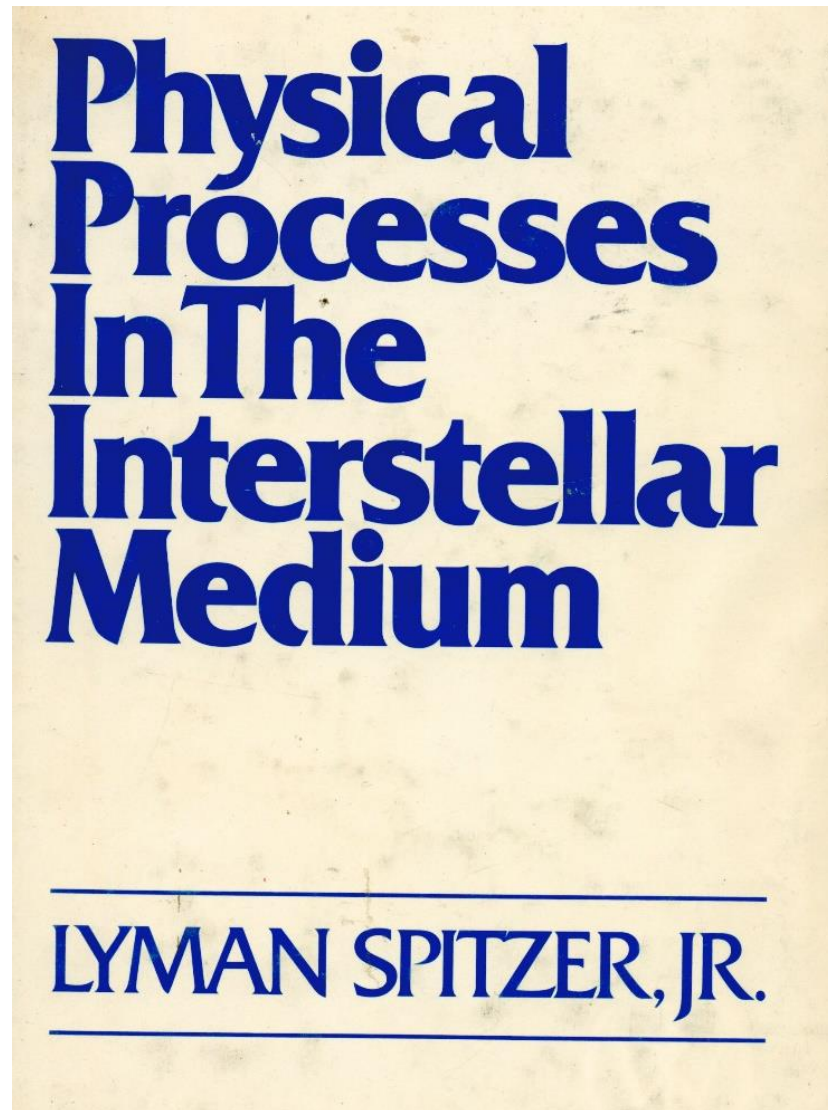
xii	CONTENTS
24.2	Heating and Cooling of Ultrasmall Dust Grains: Temperature Spikes 290
24.3	Infrared Emission from Grains 293
24.4	Collisionally Heated Dust 295
25.	Grain Physics: Charging and Sputtering 296
25.1	Collisional Charging 296
25.2	Photoelectric Emission 297
25.3	Grain Charging in the Diffuse ISM 299
25.4	★ Secondary Electron Emission 299
25.5	★ Electron Field Emission 301
25.6	★ Ion Field Emission and Coulomb Explosions 302
25.7	Sputtering in Hot Gas 302
26.	Grain Dynamics 304
26.1	Translational Motion 304
26.2	Rotational Motion 307
26.3	★ Alignment of Interstellar Dust 310
27.	Heating and Cooling of H II Regions 315
27.1	Heating by Photoionization 315
27.2	Other Heating Processes 317
27.3	Cooling Processes 319
27.4	Thermal Equilibrium 322
27.5	Emission Spectrum of an H II Region 324
27.6	Observed Temperatures in H II Regions 325
28.	The Orion H II Region 326
28.1	Trapezium Stars 326
28.2	Distribution of Ionized Gas 327
28.3	Orion Bar 328
28.4	Gas Kinematics 328
28.5	PIGS, Proplyds, and Shadows 330
29.	HI Clouds: Observations 331
29.1	21-cm Line Observations 331
29.2	Distribution of the HI 332
29.3	Zeeman Effect 333
29.4	Optical and UV Absorption Line Studies 335
29.5	Infrared Emission 335
30.	HI Clouds: Heating and Cooling 337
30.1	Heating: Starlight, Cosmic Rays, X Rays, and MHD Waves 337

CONTENTS	xiii
30.2 Photoelectric Heating by Dust	338
30.3 Cooling: [C II] 158 $\mu\text{m}$ , [O I] 63 $\mu\text{m}$ , and Other Lines	339
30.4 Two “Phases” for H I in the ISM	341
30.5 Emission Spectrum of an H I Cloud	343
31. Molecular Hydrogen	344
31.1 Gas-Phase Formation of H <sub>2</sub>	344
31.2 Grain Catalysis of H <sub>2</sub>	345
31.3 Photodissociation of H <sub>2</sub>	346
31.4 Self-Shielding	348
31.5 ★ Excitation of Vibration and Rotation by UV Pumping	349
31.6 ★ Rotational Level Populations	350
31.7 ★ Structure of a Photodissociation Region	352
31.8 Dense PDRs	356
32. Molecular Clouds: Observations	357
32.1 Taxonomy and Astronomy	357
32.2 Star Counts	362
32.3 Molecular Radio Lines	362
32.4 FIR Emission from Dust	363
32.5 $\gamma$ rays	364
32.6 ★ Compact, Ultracompact, and Hypercompact H II Regions	365
32.7 ★ IR Point Sources	366
32.8 ★ Masers	366
32.9 Size–Linewidth Relation in Molecular Clouds	366
32.10 Magnetic Fields in Molecular Clouds	369
32.11 Energy Dissipation in Molecular Clouds	371
33. Molecular Clouds: Chemistry and Ionization	373
33.1 Photoionization and Photodissociation of Molecules	375
33.2 ★ Ion–Molecule Chemistry in Cold Gas	376
33.3 ★ The CH <sup>+</sup> Problem	379
34. Physical Processes in Hot Gas	381
34.1 Radiative Cooling	381
34.2 Radiative Cooling Time	384
34.3 ★ Thermal Conduction	385
34.4 ★ Cloud Evaporation in Hot Gas	386
34.5 ★ Conduction Fronts	387
35. Fluid Dynamics	389
35.1 Mass Conservation	389

	xiv
35.2 Conservation of Momentum: MHD Navier-Stokes Equation	390
35.3 Heating and Cooling	392
35.4 Electrodynamics in a Conducting Fluid: Flux-Freezing	393
35.5 ★ Virial Theorem	395
36. Shock Waves	397
36.1 Sources of Interstellar Shocks	397
36.2 Jump Conditions: Rankine-Hugoniot Relations	398
36.3 Cooling Time and Cooling Length	404
36.4 ★ Collisionless Shocks	404
36.5 ★ Electron Temperature	406
36.6 ★ Two-Fluid MHD Shocks in Low Fractional Ionization Gas	406
37. ★ Ionization/Dissociation Fronts	412
37.1 ★ Ionization Fronts: R-Type and D-Type	412
37.2 ★ Expansion of an H II Region in a Uniform Medium	416
37.3 ★ Photodissociation Fronts	419
38. ★ Stellar Winds	422
38.1 ★ Winds from Hot Stars: Stellar Wind Bubbles	422
38.2 ★ Winds from Cool Stars	426
38.3 ★ Stellar Wind Bow-Shock	427
39. Effects of Supernovae on the ISM	429
39.1 Evolution of a Supernova Remnant in a Uniform ISM	429
39.2 ★ Overlapping of SNRs	435
39.3 ★ Supernova Remnants in an Inhomogeneous Medium	436
39.4 Three-Phase Model of the ISM	437
40. ★ Cosmic Rays and Gamma Rays	440
40.1 Cosmic Ray Energy Spectrum and Composition	440
40.2 ★ Theory of Diffusive Shock Acceleration	442
40.3 ★ Injection Problem	444
40.4 ★ Upper Limits on Cosmic Ray Energy	446
40.5 ★ Cosmic Ray Propagation	447
40.6 ★ Synchrotron Emission and Supernova Remnants	448
40.7 ★ Gamma Ray Emission from Interstellar Clouds	448
40.8 ★ <sup>26</sup> Al in the ISM	449
40.9 ★ Positrons and Positronium in the ISM	450
41. Gravitational Collapse and Star Formation: Theory	451
41.1 Gravitational Instability: Jeans Instability	451

CONTENTS	xv
41.2 ★ Parker Instability	453
41.3 Insights from the Virial Theorem	456
41.4 Magnetic Flux Problem: Ambipolar Diffusion	459
41.5 Angular Momentum Problem	461
41.6 Accretion Disks	463
41.7 Radiation Pressure	463
42. Star Formation: Observations	465
42.1 Collapse of Cores to form Stars	465
42.2 Class 0, I, II, and III Protostars	466
42.3 Initial Mass Function	468
42.4 Star Formation Rates	470
42.5 Schmidt-Kennicutt Law	471
Appendices	
A. List of Symbols	473
B. Physical Constants	476
C. Summary of Radiative Processes	477
D. Ionization Potentials (eV)	481
E. Energy-Level Diagrams	482
F. Collisional Rate Coefficients	496
G. Semiclassical Atom	503
H. Debye Length for a Plasma	505
I. Heuristic Model for Ion–Electron Inelastic Scattering	506
J. Virial Theorem	508
Bibliography	511
Index	529





## Contents

<b>Chapter 1</b>	<b>Interstellar Matter—An Overview</b>	<b>1</b>
1.1	Neutral Gas, 1	
1.2	Photon-Ionized Gas, 5	
1.3	Collision-Ionized Gas, 8	
1.4	Magnetic Fields and Cosmic Rays, 10	
1.5	Galactic Distribution, 11	
1.6	Gravitational Mass, 15	
<b>Chapter 2</b>	<b>Elastic Collisions and Kinetic Equilibrium</b>	<b>18</b>
2.1	Inverse-Square Forces, 19	
2.2	Short-Range Forces, 22	
2.3	Velocity Distribution Function, 25	
2.4	Thermodynamic Equilibrium, 28	
<b>Chapter 3</b>	<b>Radiative Processes</b>	<b>32</b>
3.1	Radiative Transfer, 32	
3.2	Emission and Absorption Coefficients, 34	
a.	Absorption coefficient $\kappa_\nu$ , 36	
b.	Effect of stimulated emission on $\kappa_\nu$ , 39	
3.3	Emission Lines, 40	
a.	Optical recombination lines, 40	
b.	Hydrogen 21-cm emission line, 42	
c.	Radio maser lines, 44	
3.4	Absorption Lines, 46	
a.	Hydrogen 21-cm line, 47	
b.	Wide H and H <sub>2</sub> optical lines, 50	
c.	Narrow optical lines, 51	

- 3.5 Continuous Emission and Absorption by Thermal Electrons, 57
  - a. Free-free radio and X-ray emission, 59
  - b. Continuous absorption of radio sources, 60
- 3.6 Refraction by Free Electrons, 61
  - a. Dispersion of pulsar signals, 61
  - b. Interstellar scintillation, 63
  - c. Faraday rotation, 65

## Chapter 4 Excitation 70

- 4.1 Excitation by Collisions, 71
  - a. Collisional rate coefficients, 71
  - b. Theory for systems with two or three levels, 76
  - c. Optical emission lines observed from heavy atoms, 78
  - d. Molecular radio lines, 81
- 4.2 Excitation by Recombination, 87
  - a. Lower quantum levels, 88
  - b. Higher quantum levels, 89
  - c. Radio recombination lines, 91
- 4.3 Photon Pumping, 94
  - a. Atomic levels, 95
  - b.  $H_2$  rotational levels, 96

## Chapter 5 Ionization and Dissociation 103

- 5.1 Ionization of Hydrogen, 105
  - a. Absorption and recombination coefficients, 105
  - b. H II regions without dust, 107
  - c. Effect of dust on H II regions, 111
  - d. Ionization by energetic particles, 114
- 5.2 Ionization of Heavy Atoms, 116
  - a. Photon ionization, 117
  - b. Collisional ionization, 118
  - c. Charge exchange and reactions with molecules, 119
- 5.3 Formation and Dissociation of Molecules, 122
  - a. Equilibrium abundance of  $H_2$ , 123

- b. Equilibrium of HD, 126
- c. Other molecules, 127

## Chapter 6 Kinetic Temperature 131

- 6.1 H II Regions, 133
  - a. Heating function  $\Gamma$ , 134
  - b. Cooling function  $\Lambda$  and resultant  $T_E$ , 136
- 6.2 H I Regions, 139
  - a. Cooling function  $\Lambda$ , 140
  - b. Heating function  $\Gamma$ , 142

## Chapter 7 Optical Properties of Grains 149

- 7.1 Optical Efficiency Factors, 151
- 7.2 Selective Extinction, 154
  - a. Spatial distribution of grains, 154
  - b. Variation of extinction with wavelength, 157
- 7.3 General Extinction, 160
  - a. Ratio of general-to-selective extinction, 160
  - b. Mean density and surface area of grains, 161
  - c. Visible nebulae and representative clouds, 163
- 7.4 Scattering, 164
  - a. Diffuse galactic light, 164
  - b. Scattered light in H II regions, 165
- 7.5 Infrared Emission, 166

## Chapter 8 Polarization and Grain Alignment 171

- 8.1 Optical Properties of Nonspherical Particles, 172
- 8.2 Observed Polarization, 174
  - a. Dependence on color excess, 174
  - b. Dependence on wavelength, 175
  - c. Dependence on galactic longitude, 178
  - d. Circular polarization, 181
- 8.3 Alignment, 182
  - a. Conservative torques, 183
  - b. Accelerating collisional torques, 185
  - c. Retarding magnetic torque, 187

- 9.1 Temperature of the Solid Material, 191
  - a. H I regions, 192
  - b. H II regions, 195
- 9.2 Electric Charge, 198
  - a. Electron and ion collisions, 198
  - b. Photoelectric emission, 199
- 9.3 Radiative Acceleration, 201
  - a. Gyration around magnetic field, 202
  - b. Dynamical friction with gas, 203
- 9.4 Evolution of Grains, 205
  - a. Formation and growth, 205
  - b. Denudation and disruption, 209

**Chapter 10 Dynamical Principles****214**

- 10.1 Basic Equations, 214
  - a. Virial theorem, 217
- 10.2 Shock Fronts, 218
  - a. Perfect gas,  $\mathbf{B}=0$ , 219
  - b. Hydromagnetic shocks, 221
- 10.3 Instabilities, 222
  - a. Rayleigh-Taylor instability, 223

**Chapter 11 Overall Equilibrium****226**

- 11.1 Parameters of the Interstellar Gas, 226
  - a. Physical state, 226
  - b. Energy source for cloud motions, 230
- 11.2 Galactic Equilibrium, 232
  - a. Spherically symmetric system, 232
  - b. Plane one-dimensional system, 233
  - c. Equilibrium in a plane gravitational potential, 235
- 11.3 Equilibrium of Clouds, 239
  - a. Spherical cloud,  $\mathbf{B}=0$ , 241
  - b. Magnetized cloud, 242

**Chapter 12 Explosive Motions****246**

- 12.1 H II Regions, 246
  - a. Ionization fronts, 247
  - b. Initial ionization of the gas, 249
  - c. Expansion of the ionized gas, 251
- 12.2 Supernova shells, 255
  - a. Initial expansion of supernova material, 255
  - b. Intermediate nonradiative expansion, 257
  - c. Late isothermal expansion, 259
  - d. Numerical solutions, 261
- 12.3 Effect of explosions on clouds, 262
  - a. H I cloud engulfed by an H II ionization front, 262
  - b. H I cloud engulfed by a shock front, 266

**Chapter 13 Gravitational Motion****270**

- 13.1 Accretion, 270
  - a. Uniform streaming of a cold gas, 270
  - b. Spherical adiabatic inflow, 272
  - c. Uniform adiabatic streaming, 275
- 13.2 Spiral Density Waves, 276
  - a. Equations for gas motion in a spiral disk, 277
  - b. Occurrence of shock fronts, 280
- 13.3 Gravitational Condensation and Star Formation, 281
  - a. Gravitational instability, 282
  - b. Gravitational collapse of a sphere, 286
  - c. Fragmentation, 288
  - d. Transfer of angular momentum, 291
  - e. Decrease of magnetic flux, 293

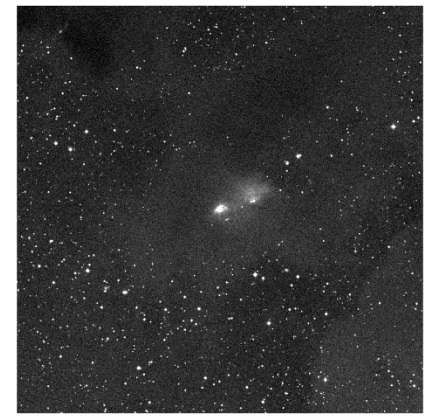
x	CONTENTS	
	Cyclic activity	196
	<i>Sunspot cycle</i>	196
	<i>Other cycles</i>	200
4A.4	Solar neutrinos	201
4A.5	Solar corona	203
	Morphology	203
	Coronal optical spectrum	205
	Coronal x-rays	206
	Physical conditions	206
	Coronal energy	207
	Problems	208
<b>5A</b>	<b>Stellar winds</b>	<b>210</b>
	Summary	210
	Introduction	210
5A.1	The solar wind	211
5A.2	Stellar winds	213
	Observations	213
	Theory	215
	Problems	223
<b>6P</b>	<b>Physical background</b>	<b>224</b>
	Summary	224
6P.1	Masers	224
6P.2	Synchrotron radiation	226
<b>6A</b>	<b>H II regions and related objects</b>	<b>235</b>
	Summary	235
	Introduction	235
6A.1	H II regions: theory	235
6A.2	H II regions: physical properties	246
6A.3	H II regions: formation and evolution	252
6A.4	H II regions as distance yardsticks	254
6A.5	Planetary nebulae	254
6A.6	Supernova remnants	258
	Problems	262
<b>7A</b>	<b>The interstellar medium</b>	<b>264</b>
	Summary	264
	Introduction	264
7A.1	Basic properties	265
7A.2	Dust grains	267
7A.3	Interstellar gas	274

	CONTENTS	xi
7A.4	Cosmic rays	282
	Primary cosmic rays	282
	Secondary cosmic rays	290
	Solar cosmic rays	293
	<i>Solar particle emission</i>	293
	<i>Solar cosmic ray modulation</i>	296
	Problems	298
<b>8A</b>	<b>Stellar formation and evolution</b>	<b>299</b>
	Summary	299
	Introduction	299
8A.1	Star formation	303
8A.2	Post-main-sequence evolution	309
	Low-mass stars	309
	Medium-mass stars	310
	Binary systems	314
	High-mass stars	318
<b>Appendix I</b>	Distances of the stars	321
<b>Appendix II</b>	Notes	327
<b>Appendix III</b>	Bibliography	337
<b>Appendix IV</b>	Symbols and constants	344
<b>Appendix V</b>	Answers to the problems	346
<b>Index</b>		349

# 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  $\delta$  Orionis  $\rightarrow$  of interstellar origin
- 1919 E. E. Barnard catalog of dark nebulae
- Photography  $\rightarrow$  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  $\nearrow$  as distance  $\nearrow$   
 $\rightarrow$  beginning of ISM as a new branch of astronomy

# INVESTIGATIONS ON THE SPECTRUM AND ORBIT OF $\delta$ ORIONIS.<sup>1</sup>

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  $\delta$  *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<sup>2</sup> 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  $\delta$  *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.

$\lambda$	No. of Plates	Mean Error	Remarks
3933.68	7	( $\pm 0.34$ )	<i>Ca</i> ; always exceedingly weak and narrow.
4069.49	3	$\pm 0.16$	
4097.49	5	0.14	<i>Si</i>
4116.28	11	0.07	<i>Si</i>
4144.94	2	0.28	
4200.42	2	0.20	<i>H</i> $\delta'$ according to Pickering's nomenclature.
4541.78	2	0.41	<i>H</i> $\gamma'$ 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  $\lambda$  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 wavelengths 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  $\lambda$  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  $\delta$  *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  $\lambda 3934$  and  $\lambda 3969$ , 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  $\delta$  *Orionis* also it is not unlikely that the cloud stands in some relation to the extensive nebulous masses shown by Barnard<sup>1</sup> to be present in the neighborhood. The second calcium line at  $\lambda 2060$  is con-



# THE ASTROPHYSICAL JOURNAL

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AND ASTRONOMICAL PHYSICS

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NUMBER I

PLATE I

## ON THE DARK MARKINGS OF THE SKY

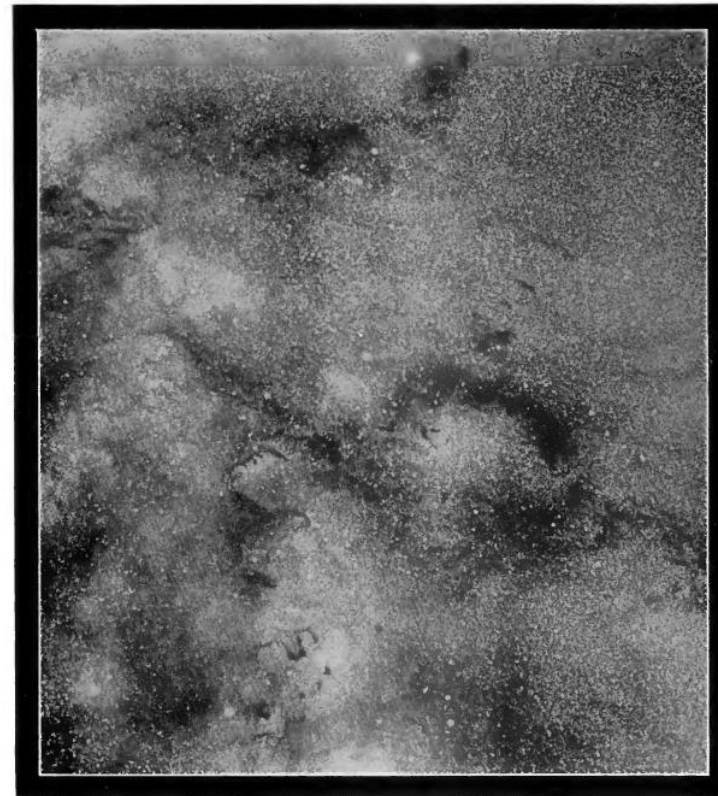
WITH A CATALOGUE OF 182 SUCH OBJECTS

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

North



REGION NORTH OF THETA OPHIUCHI

$\alpha = 17^h 13^m$ ,  $\delta = -21^\circ 0'$

Scale:  $1^{mm} = 234''$

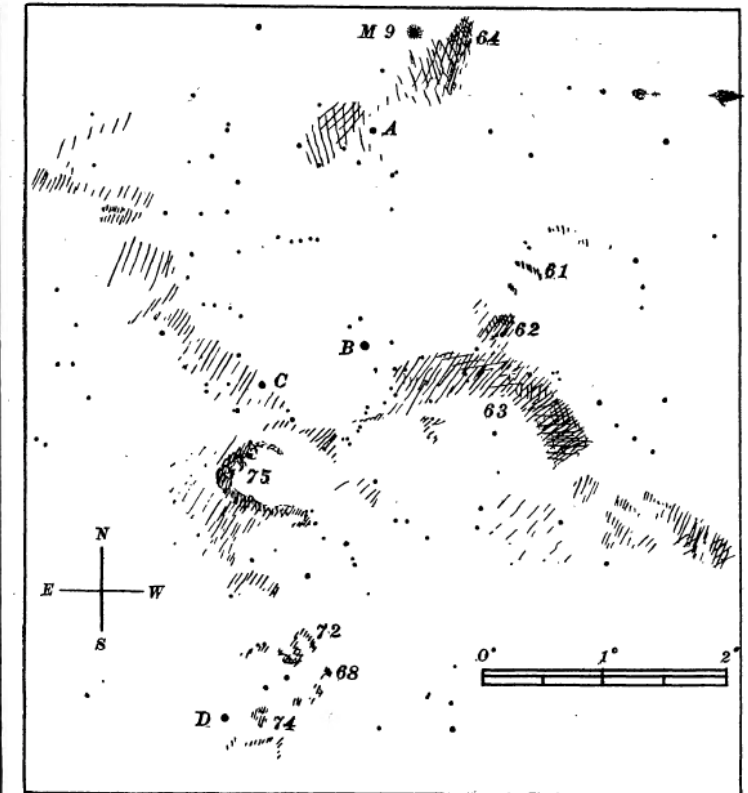


FIG. 2.—Sketch map of Plate I



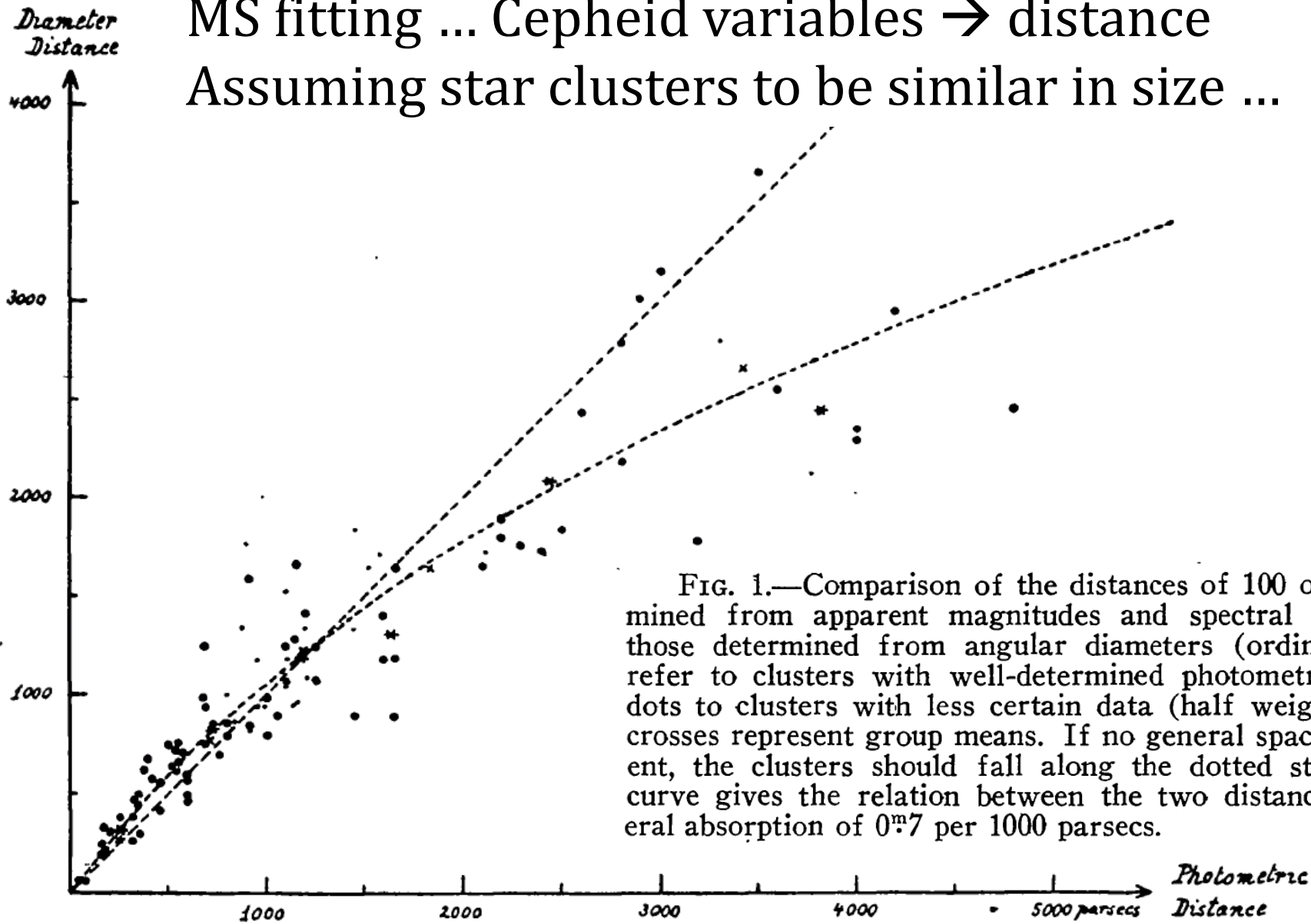
## Exercise

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.”<sup>1</sup> 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*.<sup>2</sup> 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 ...





# Barnard 72 in Ophiuchus



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





## Star Shadows Remote Observatory

Horsehead Nebula



Hubble  
Heritage

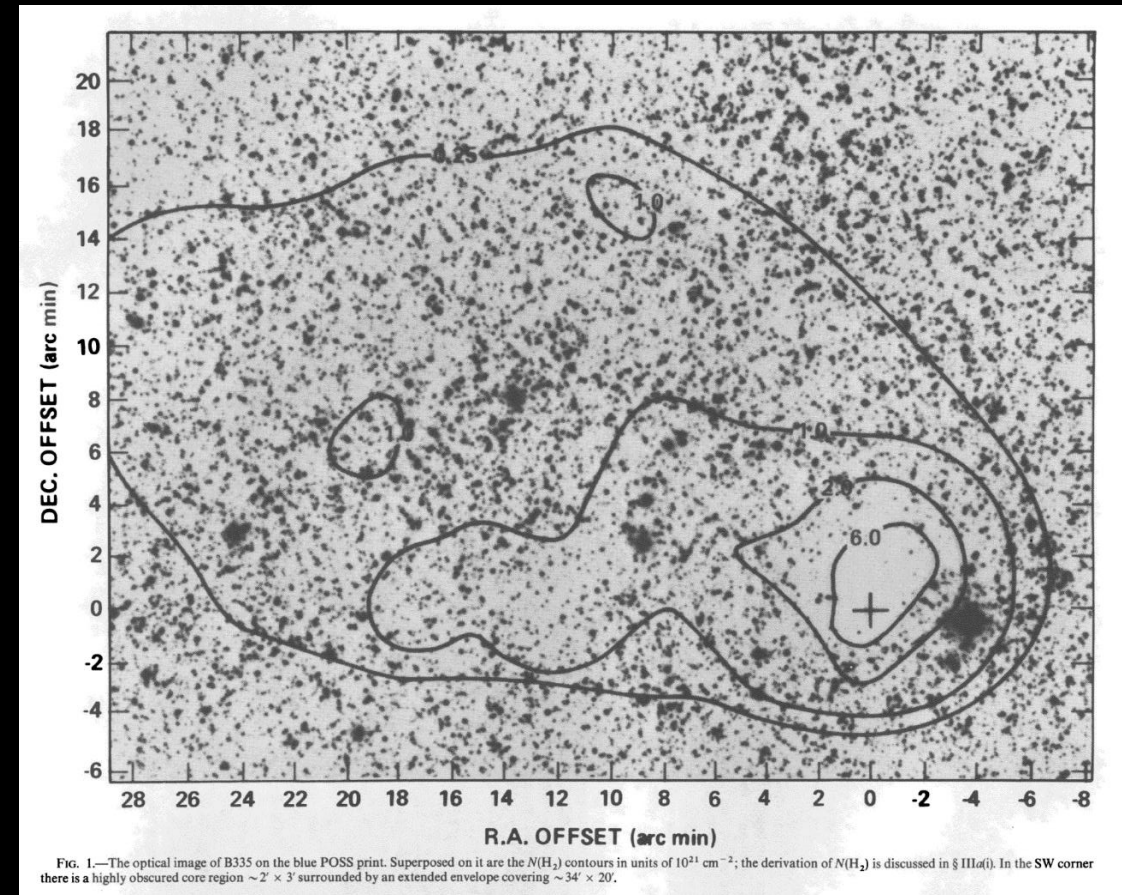
NASA, ESA, and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC01-12



(Bok) Globules silhouetted  
against emission nebulaosity



A dark cloud core seen  
against a star field





## Optical Composite



Pre-Collapse Black Cloud B68 (visual view)  
(VLT ANTU + FORS 1)

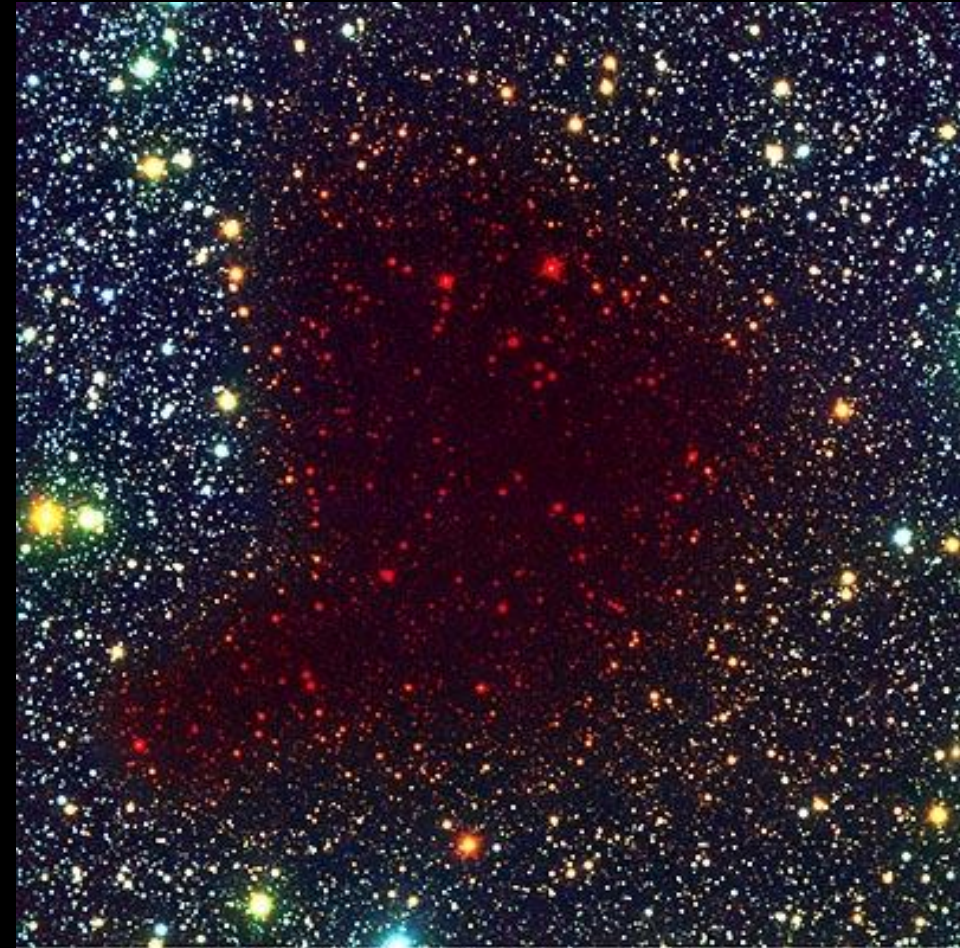
erview

ESO PR Photo 02a/01 (10 January 2001)

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## Optical/IR composite



Seeing Through the Pre-Collapse Black Cloud B68  
(VLT ANTU + FORS 1 - NTT + SOFI)

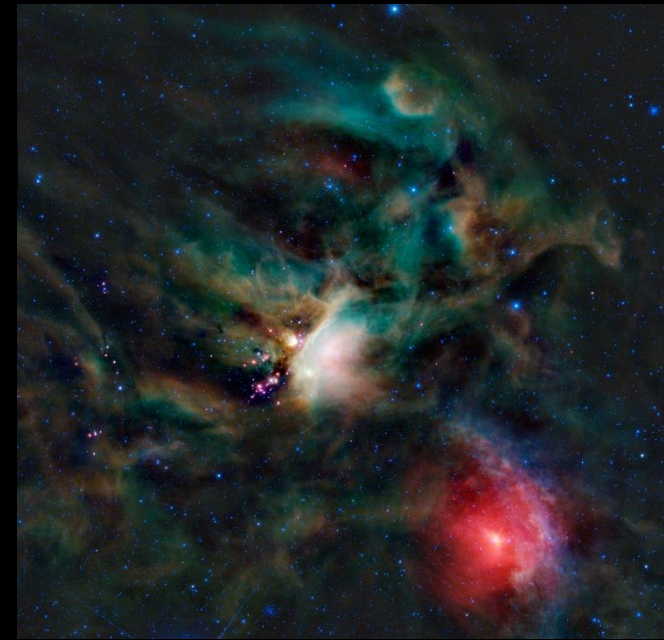
26

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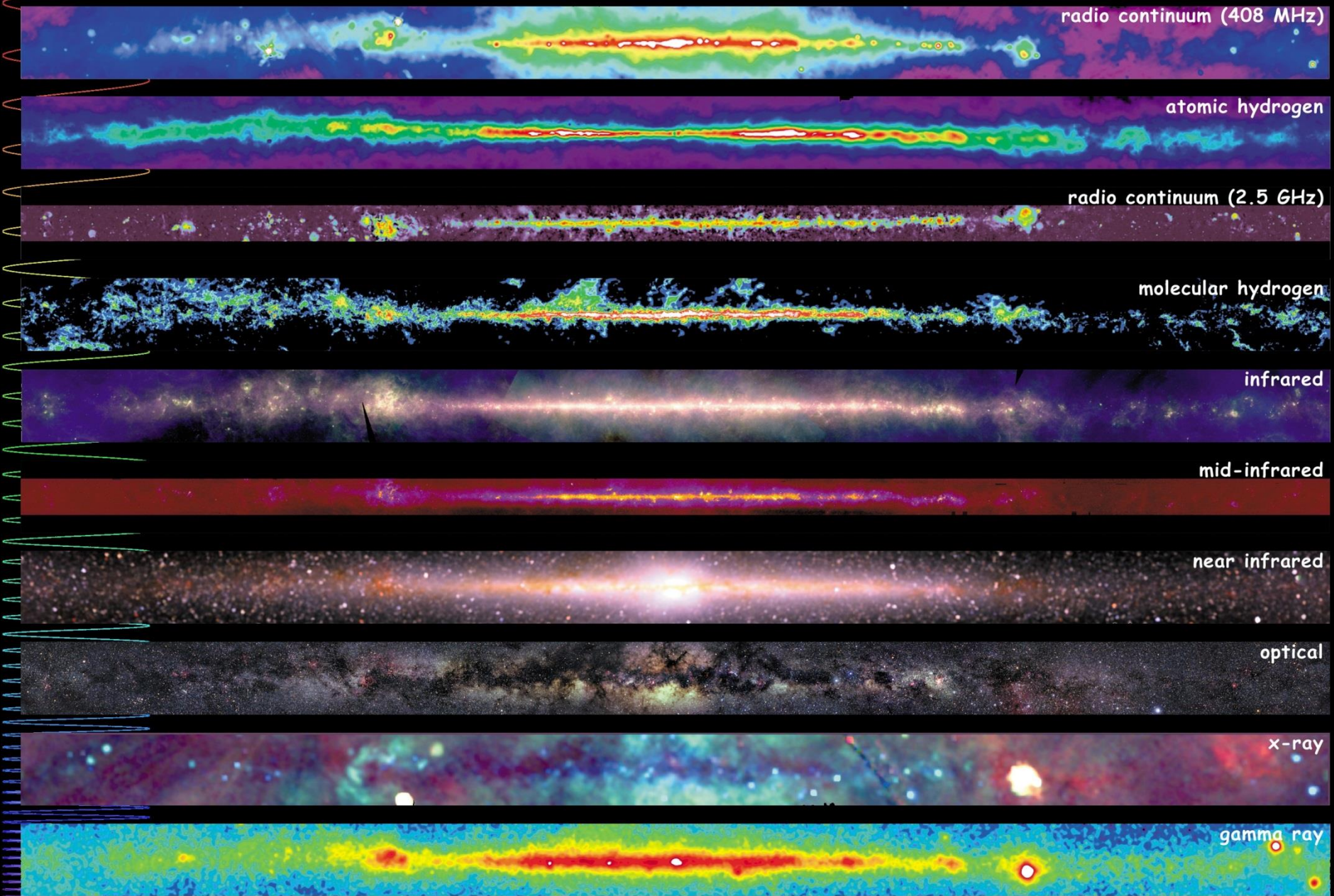
# $\rho$ Ophiuchi cloud complex



WISE

[https://en.wikipedia.org/wiki/Rho\\_Ophiuchi#/media/File:Rho\\_Ophiucus\\_Widefield.jpg](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]  
 $\sim 1 \text{ pc} / 10^{11} \text{ cm} \sim 3 \times 10^7 : 1$ ; in terms of volume (space)  $\sim 10^{22}$

*(What about galaxies?)*

➔ Stars truly tiny compared to space in between

- Mass: [gas + dust] / total  $\sim 15\%$ , 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<sub>2</sub> (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 <sup>-3</sup> )	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 <sub>2</sub> and dust
Supernova Remnants	$10^4 \sim 10^7$	$>1$	
Planetary Nebulae			

# Energy Density in the Local ISM

Component	$u$ (eV/cm <sup>-3</sup> )	Properties
Cosmic microwave background	0.265	$T_{\text{CMB}} = 2.725$ 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 <sup>-3</sup>
Magnetic field	0.89	$B^2 / 8\pi$ ; $\langle B \rangle = \mu\text{G}$
Cosmic rays	1.39	

There seems to be equipartition between these energies. Why?

Read Draine's book, page 10

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

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*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.

## A SMALL CLOUD

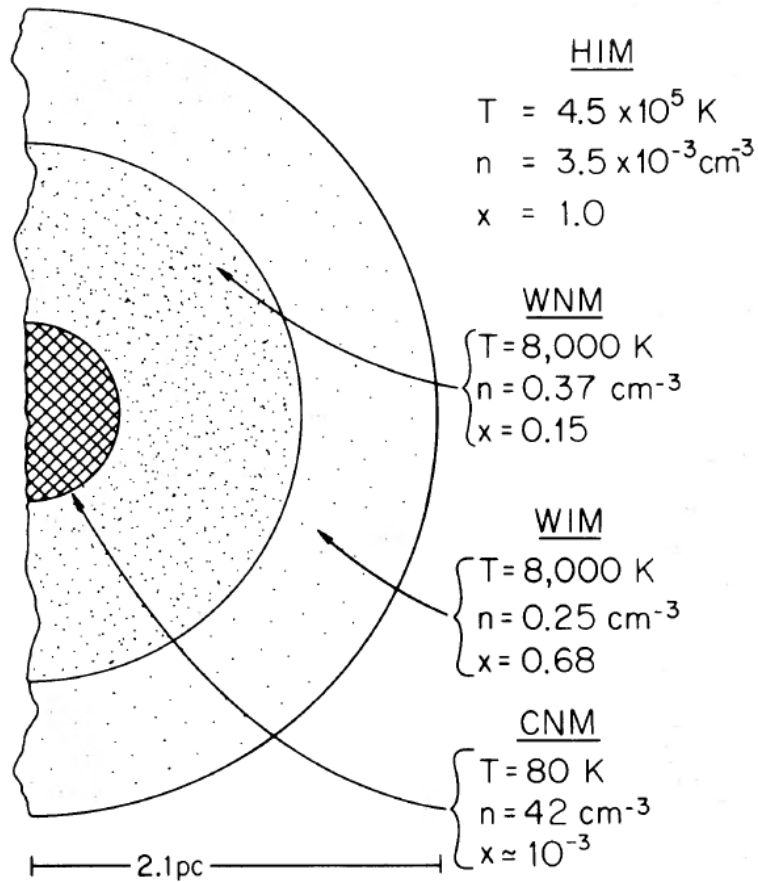
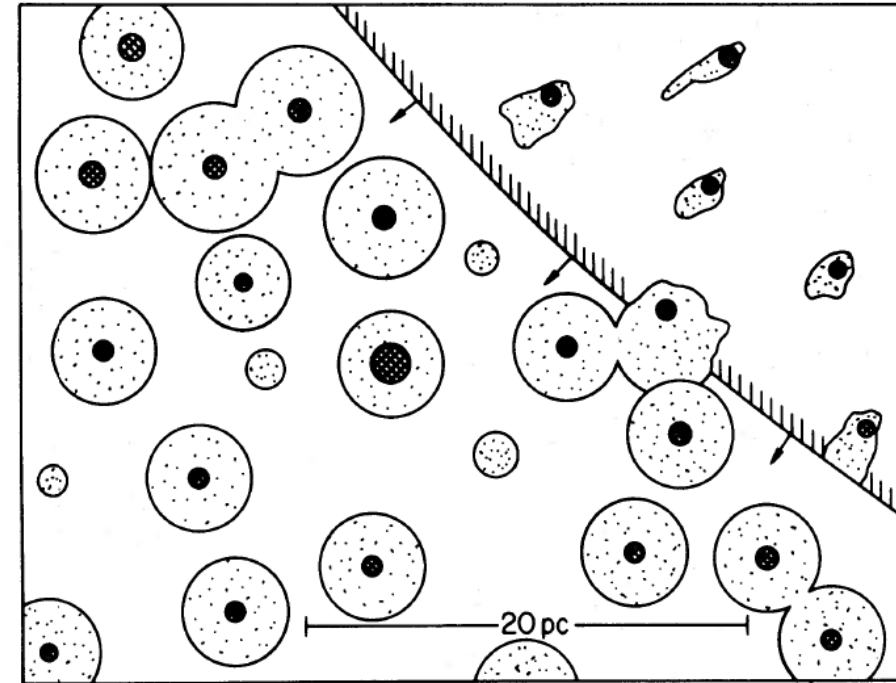


FIG. 1

## Zooming out from Fig. 1



A CLOSE UP VIEW

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  $\times$  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

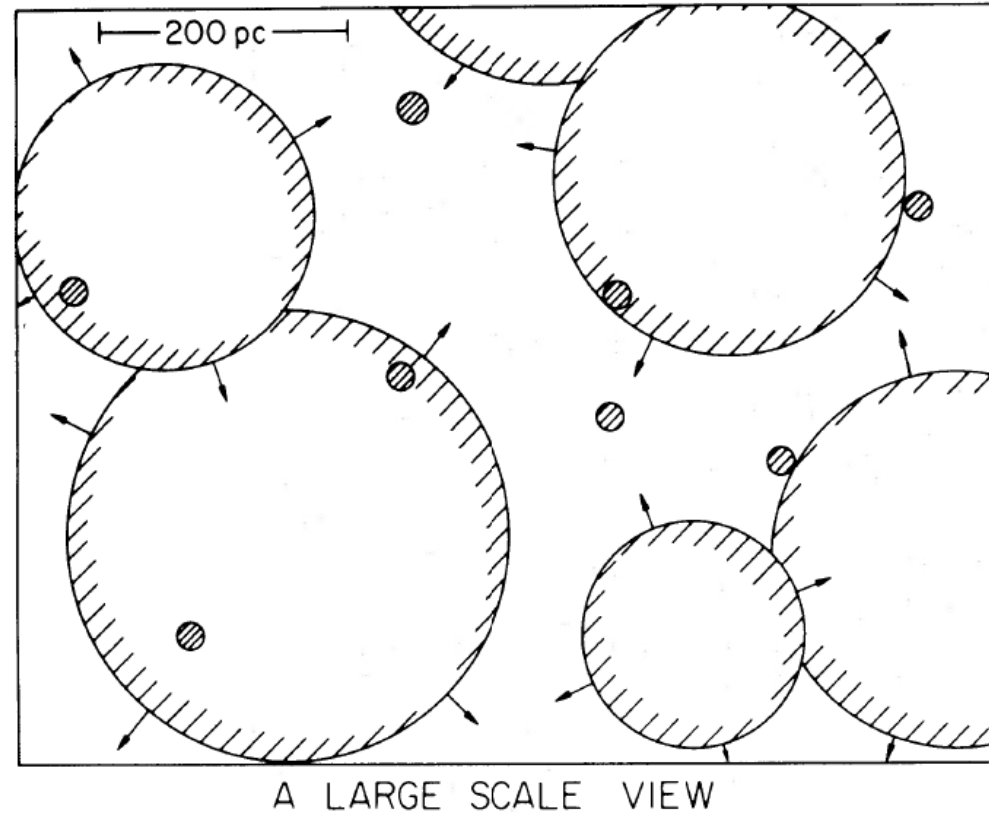


FIG. 3.—Large-scale structure of the interstellar medium. The scale here is 20 times greater than in Fig. 1: the region is 600 × 800 pc. Only SNRs with  $R < R_c = 180$  pc and clouds with  $a_0 > 7$  pc are shown. Altogether about 9000 clouds, most with  $a_w \sim 2.1$  pc, would occur in a region this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

## Exercise

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

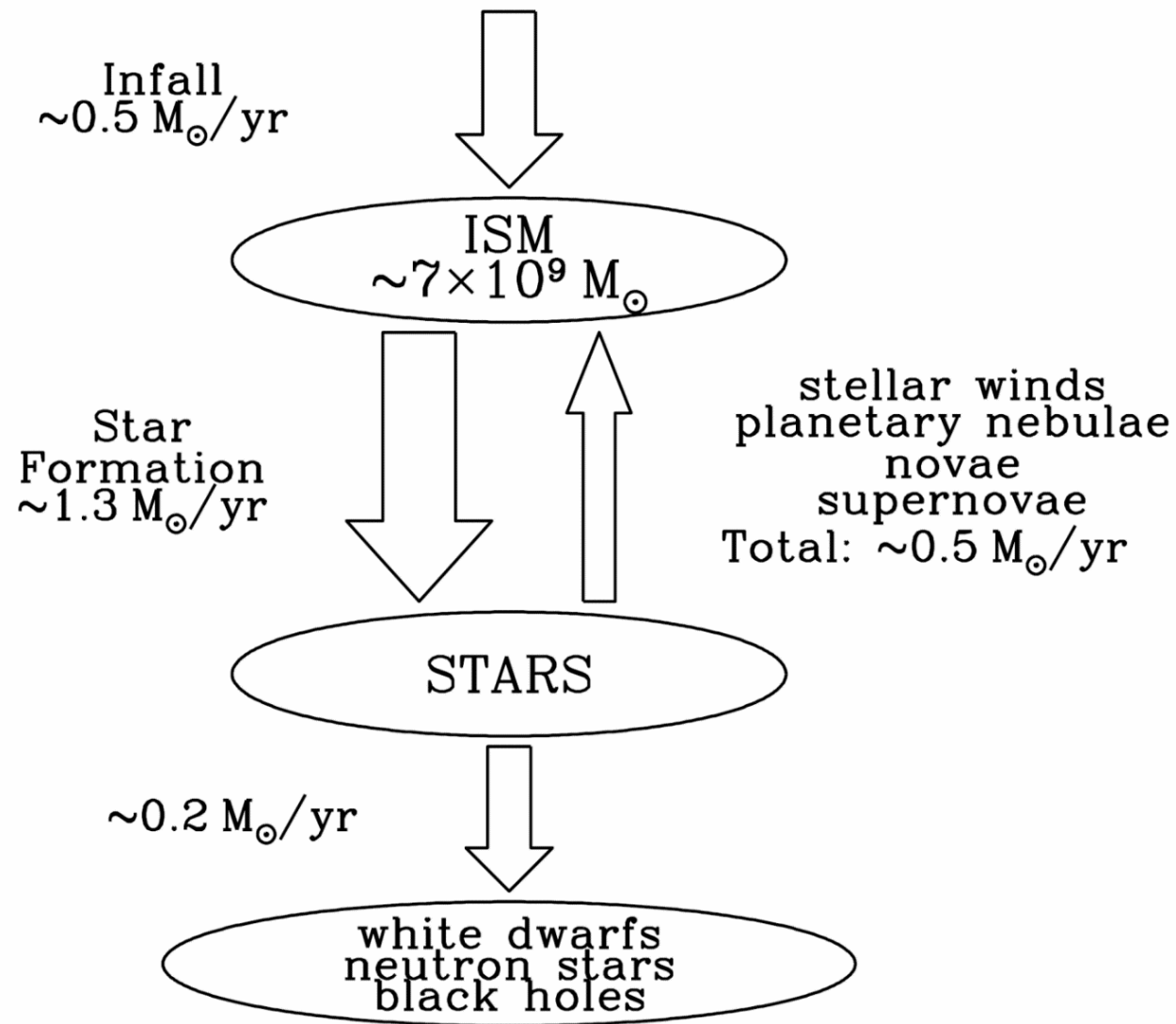
*(How are these known?)*

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

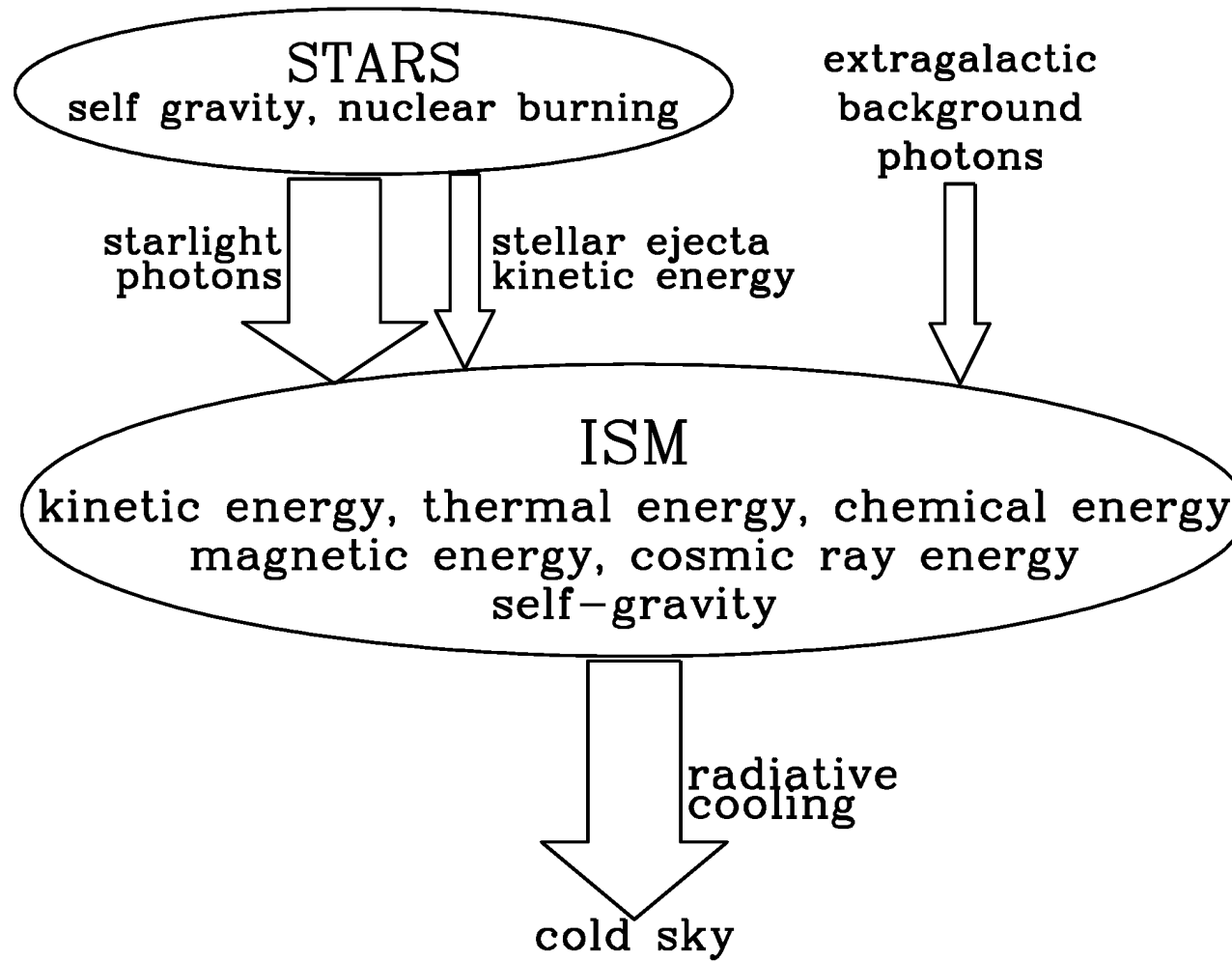
In this course, we will discuss mainly the diffuse clouds, in ionized, atomic and molecular forms, whereas the warm and hot intercloud gas will be reviewed only briefly.





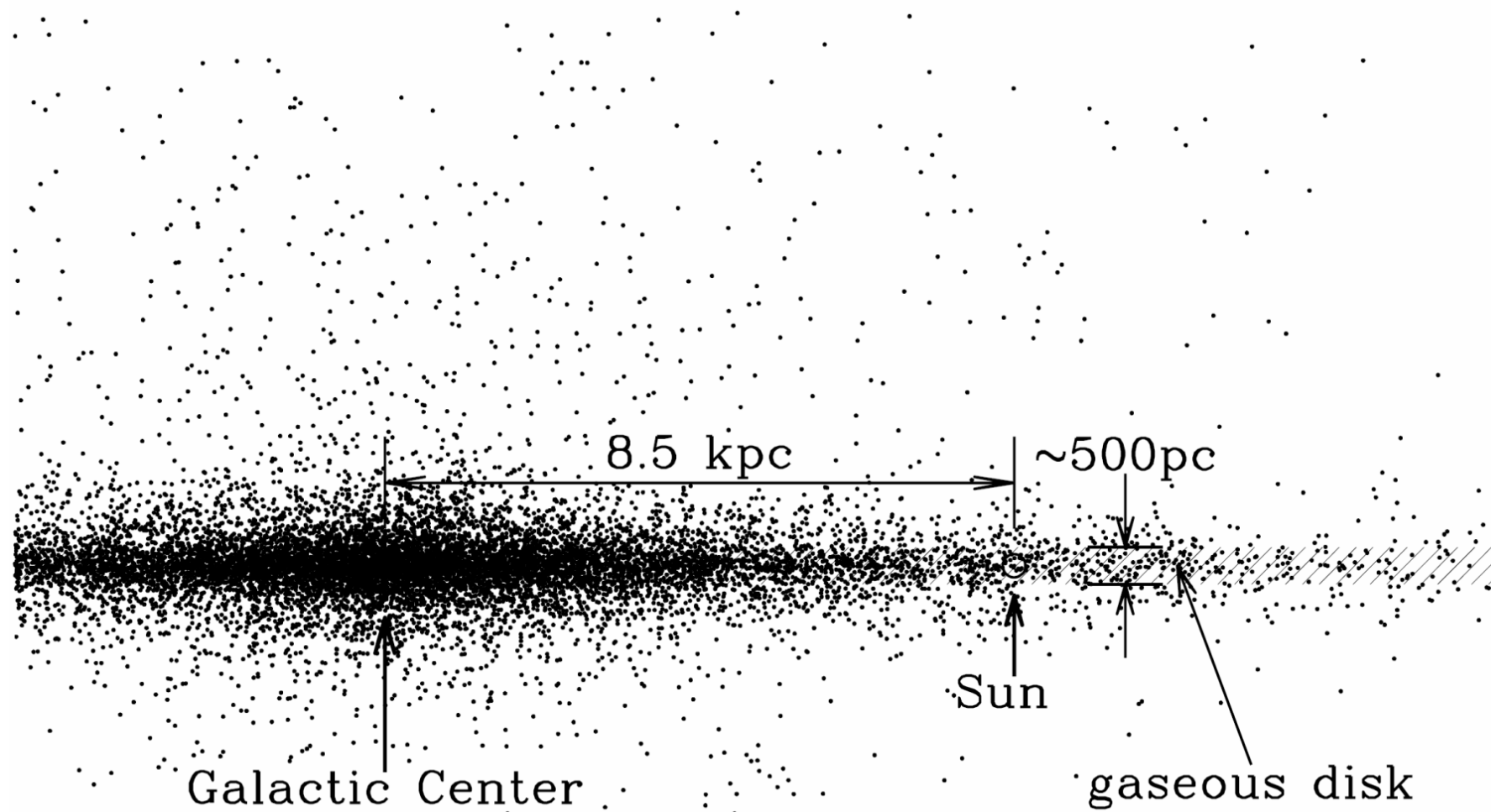


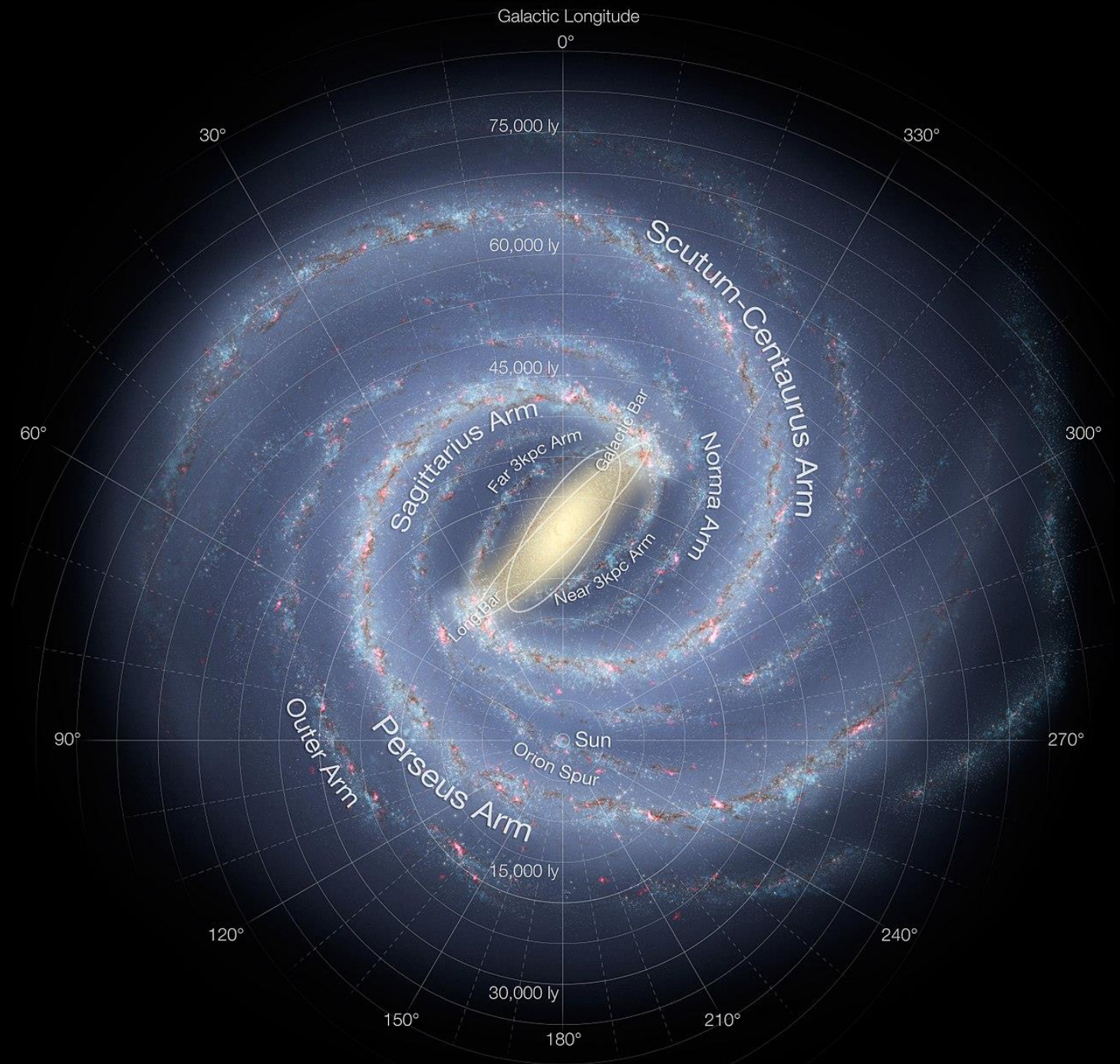
# The ISM is far from thermodynamic equilibrium.





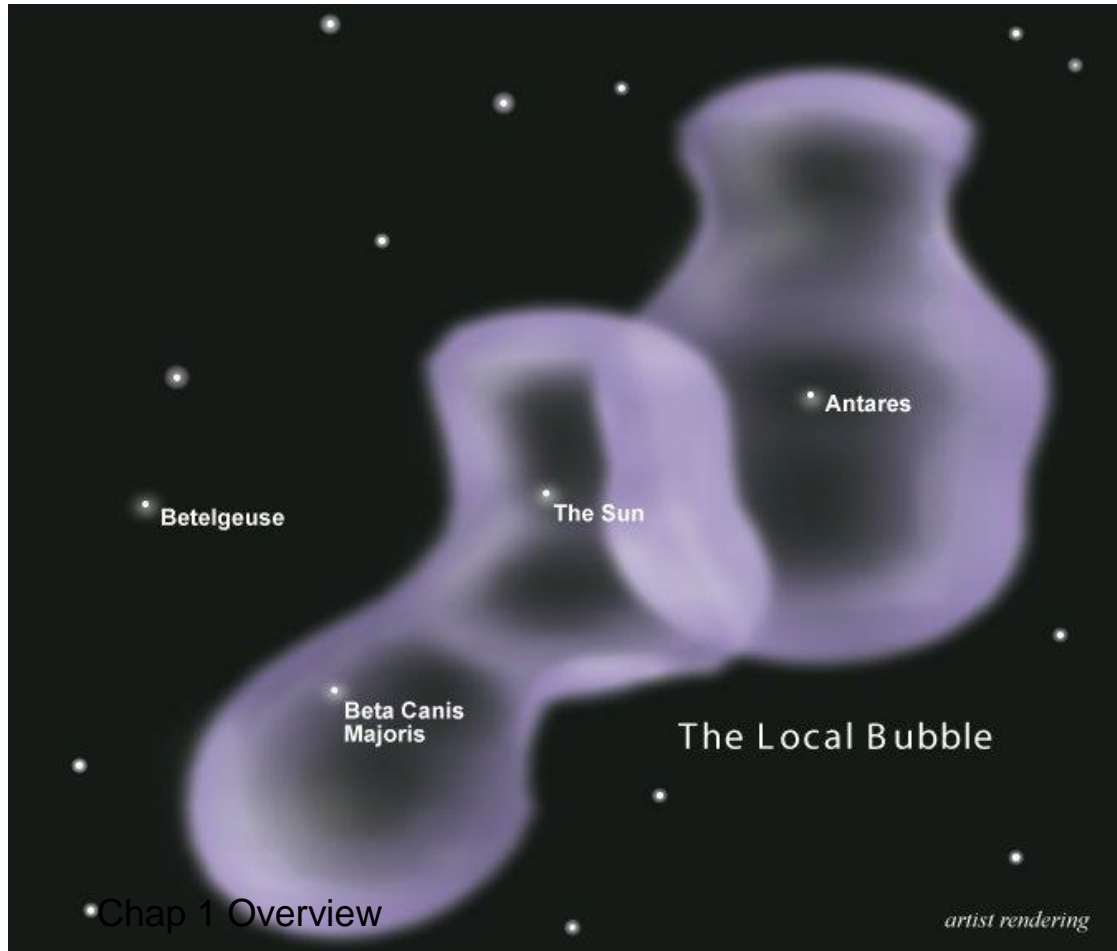




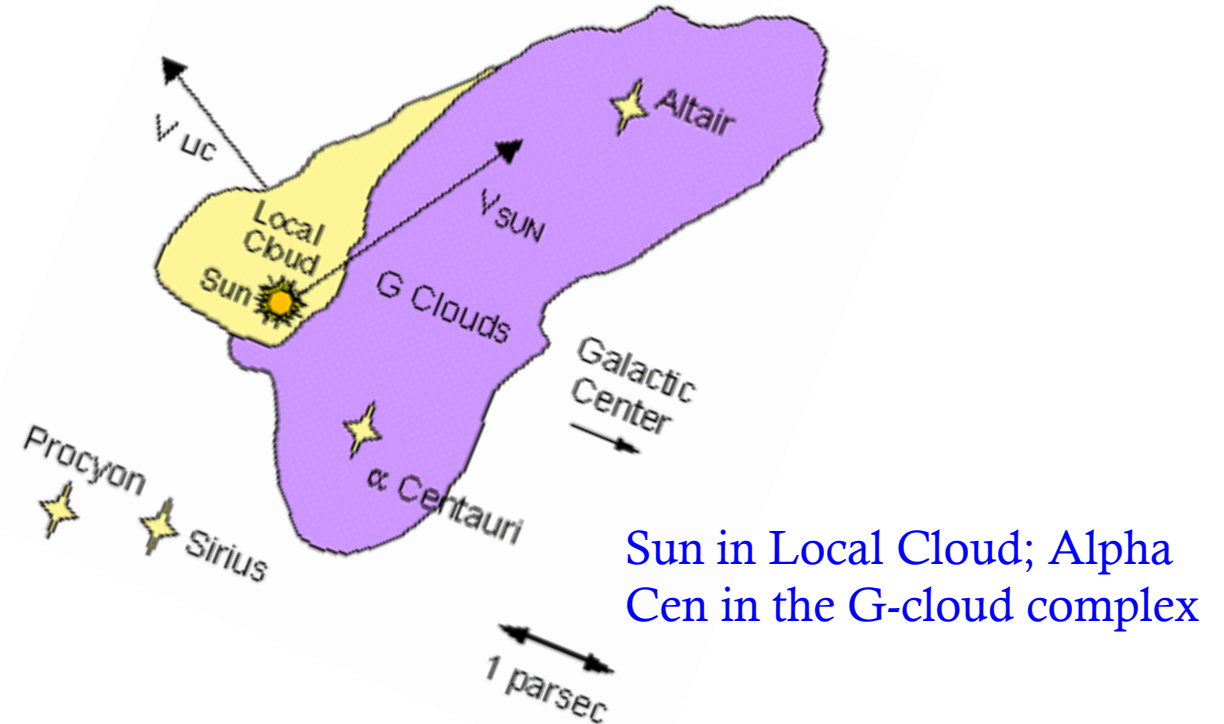




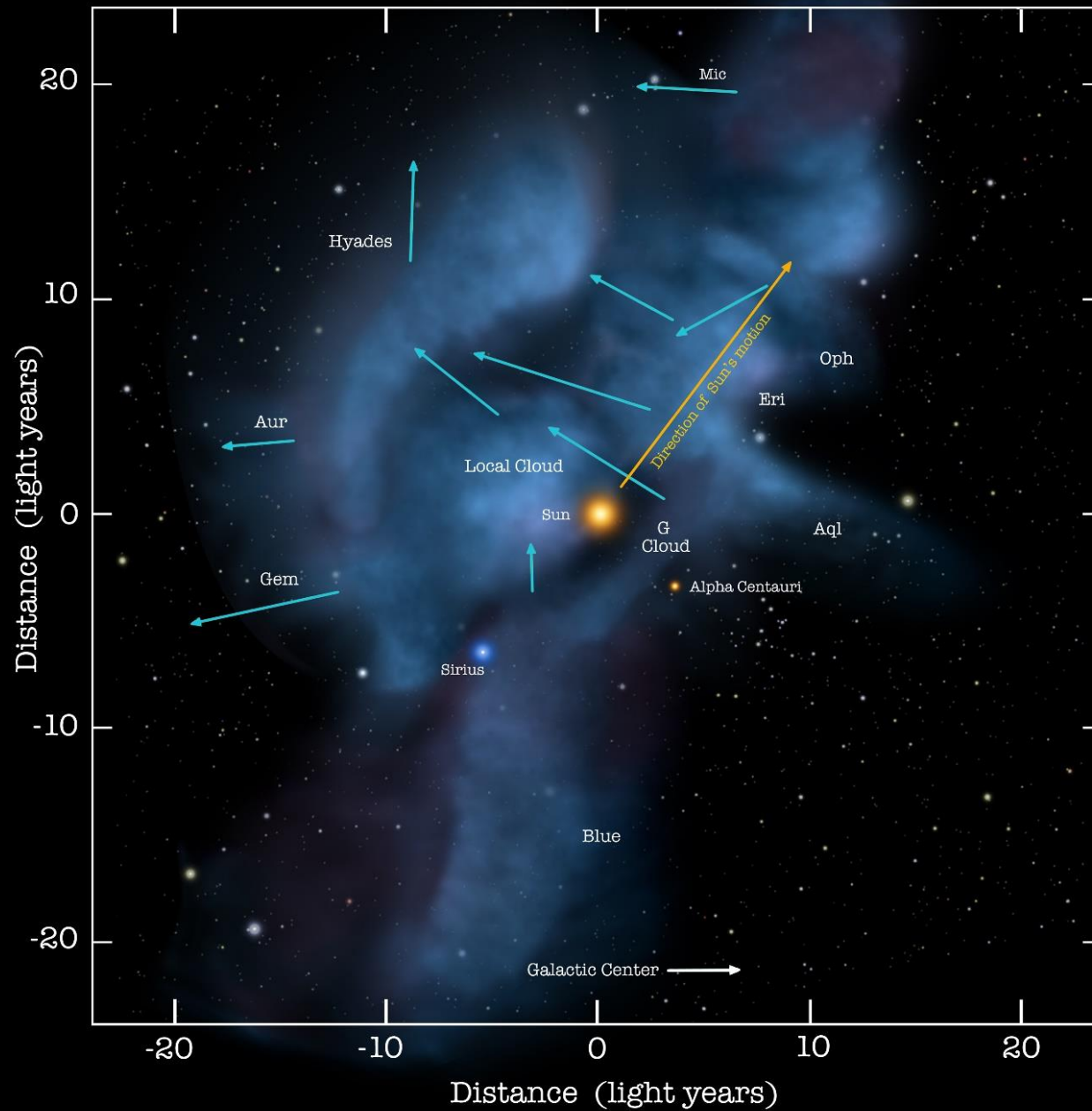
**The Local Bubble** A cavity of sparse, hot gas in the Orion Arm;  $\sim 100$  pc across;  $n \sim 0.05 \text{ cm}^{-3} \sim 0.1$  of ISM; likely by SN explosions 10--30 Myr ago?



Where is the supernova (remnant)?  
Check out the Orion-Eridanus [Superbubble](#)

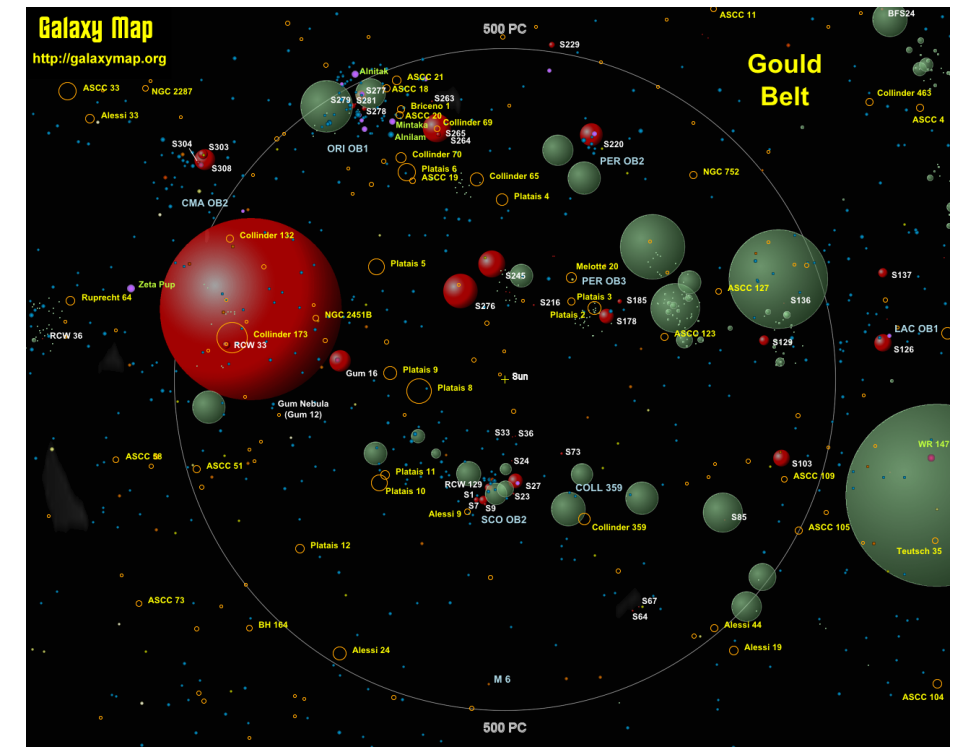


[https://en.wikipedia.org/wiki/Local\\_Bubble](https://en.wikipedia.org/wiki/Local_Bubble)

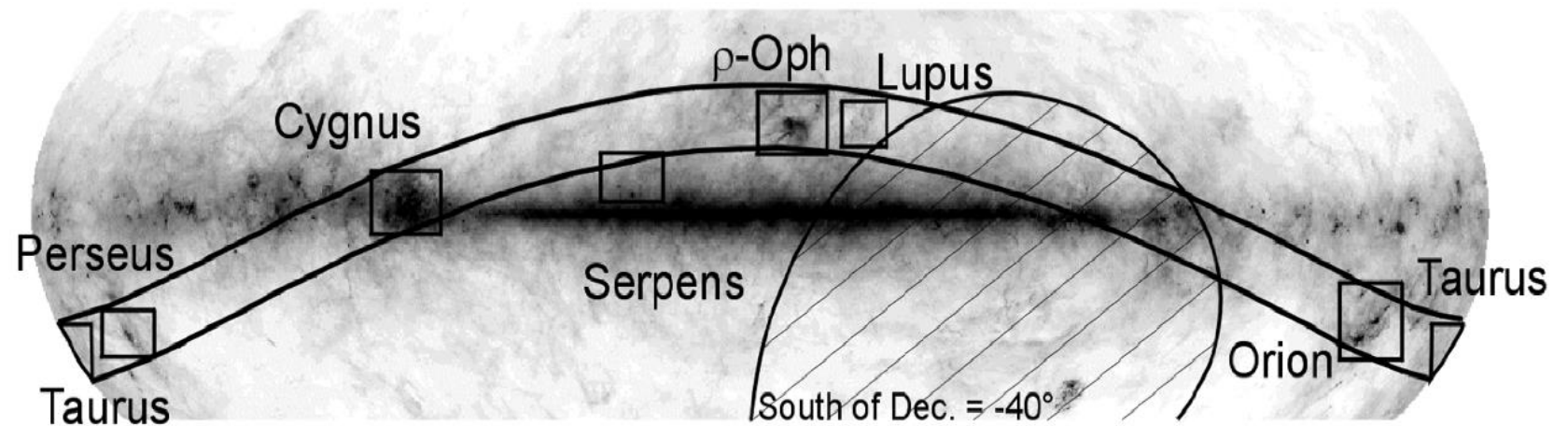
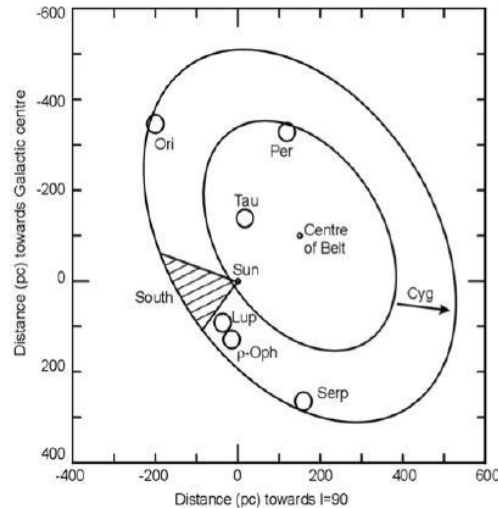


The **Gould Belt**, a (partial) ring in the sky, ~1 kpc across, centered on a point 100 pc from the Sun and tilted about 20 deg to the Galactic plane, containing star-forming molecular clouds and OB stars = local spiral arm

Origin unknown (dark matter induced star formation?)

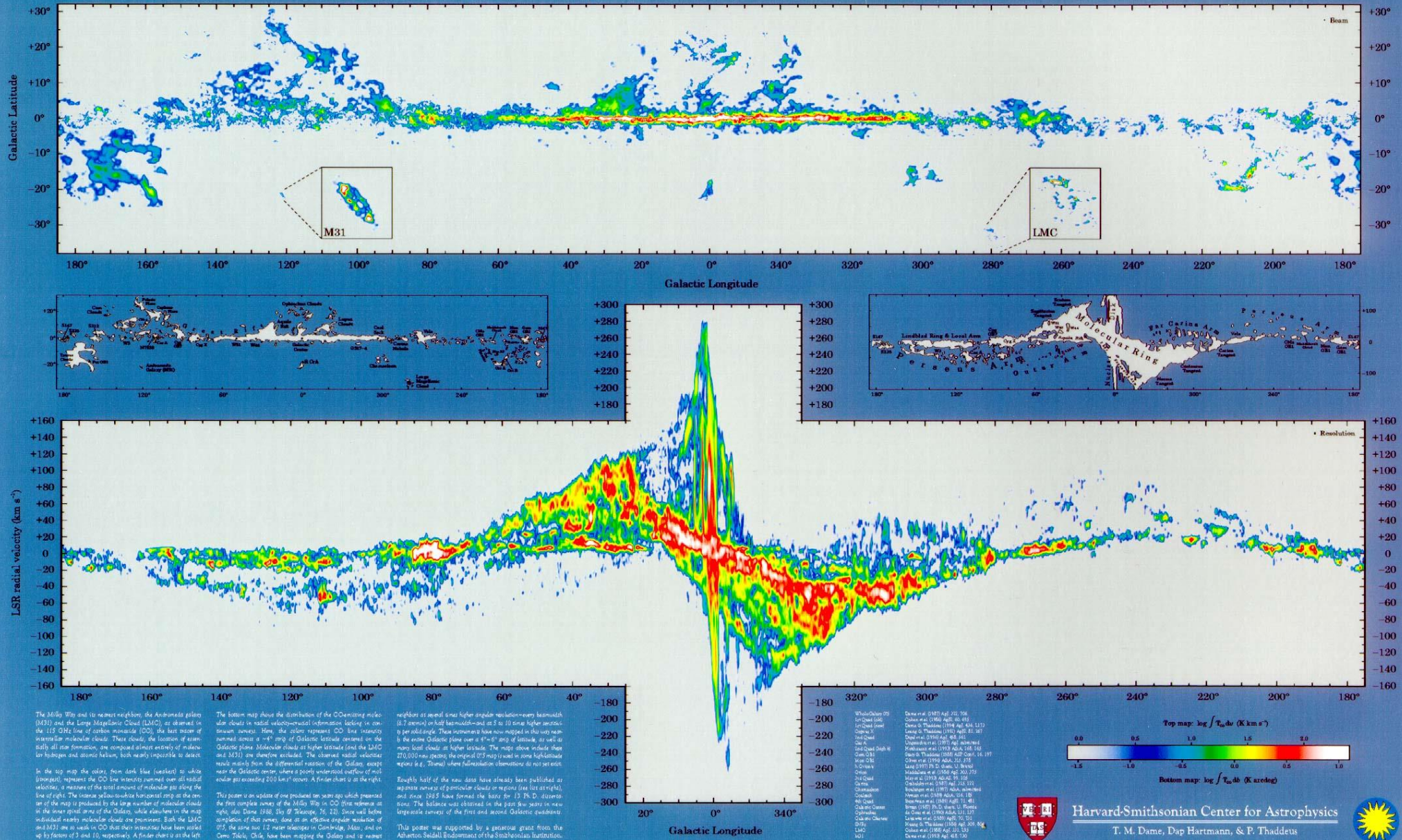


[http://galaxymap.org/detail\\_maps/download\\_maps/gould.png](http://galaxymap.org/detail_maps/download_maps/gould.png)





# The Milky Way in Molecular Clouds



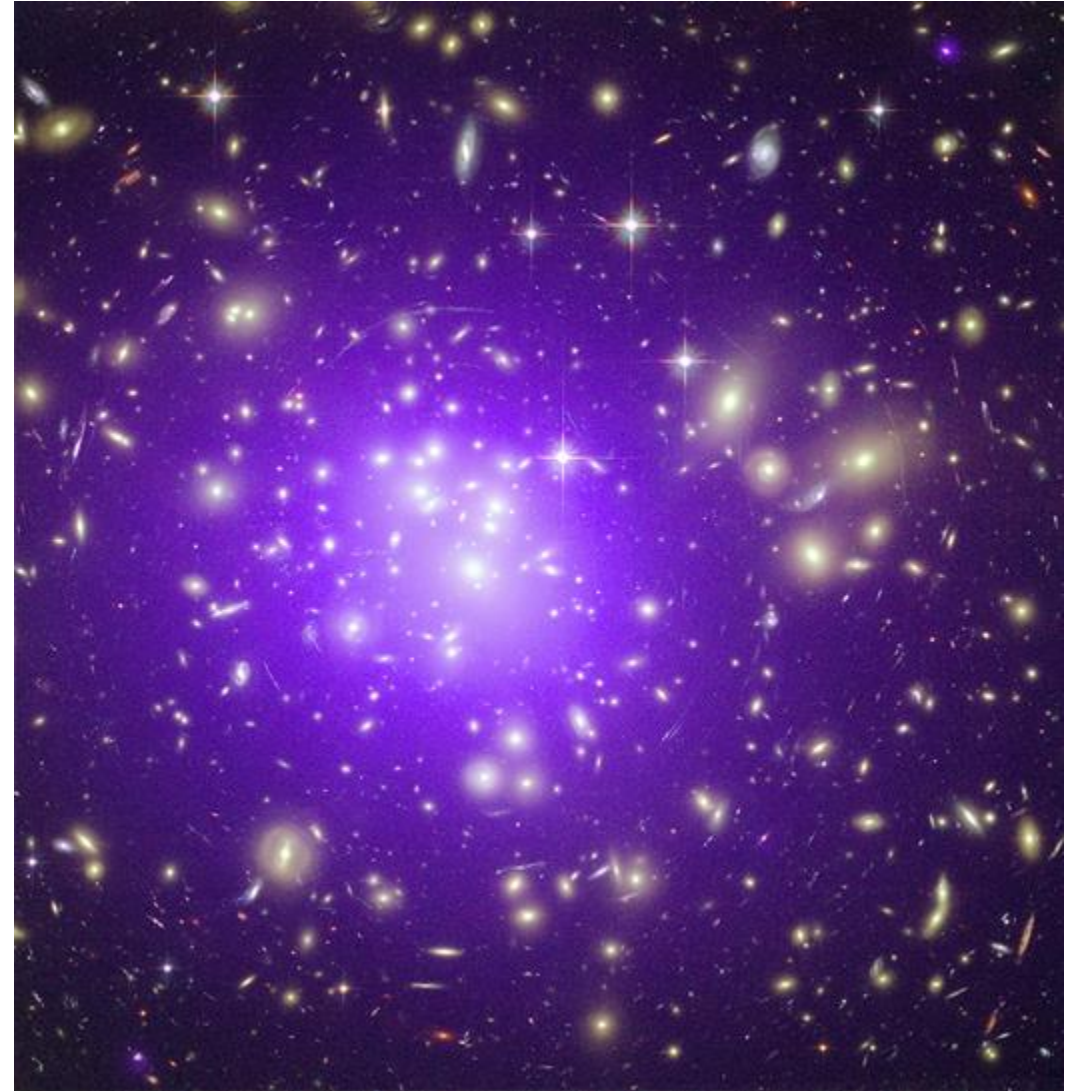


# Intergalactic medium

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

# Intracluster medium

Hot ( $10^7$  to  $10^8$  K)  
sparse ( $1000/\text{m}^3$ )



Chandra image (100 MK) of Abell1689