Physics and chemistry of the interstellar medium

Lecturers: **Simon Glover, Rowan Smith**
Tutor: **Raquel Chicharro**

- This course consists of three components:
  - Lectures [Wed., 2-4]
  - Exercises [Thu., 4-5]
  - Seminar [Wed., 5-7]

- In order to get credit points for this course, you need to complete all three components.

- Completion means:
  - Regular attendance
  - Participation in the seminar
  - Gaining sufficient marks in the exercises and final exam
    - Exercises count for 50%, exam for 50%

- Exercise sheets will be available during the lecture and also online on the course website:

www.ita.uni-heidelberg.de/~rowan/Physics_of_ISM.shtml?lang=en

- Due date will be given on sheet; typically, due by next lecture.

- Hand in during lecture (or seminar), or make alternative arrangements with Raquel

- Late/missing exercises get **zero** marks

- If you have a good reason why you are unable to hand in exercises (e.g. illness), contact Rowan or myself no later than the due date

- Contact details:
  - Simon Glover: glover@uni-heidelberg.de
  - Rowan Smith: rowan@uni-heidelberg.de

- Can also phone (numbers are on the ITA website) or visit our offices in Albert-Ueberle-Str. 2

Lecture plan

24.04 - SG - Absorption and emission of radiation
01.05 - **NO LECTURE**
08.05 - SG - Radiative transfer
15.05 - SG - Radiative heating and cooling
22.05 - SG - Galactic radiation fields
29.05 - SG - Photoionisation and recombination
06.06 - SG - HII regions
12.06 - BG - Dust *[Guest lecture by Brent Groves from MPIA]*
19.06 - RJS - HI clouds
26.06 - RJS - Molecular clouds, part 1
03.07 - RJS - Molecular clouds, part 2
10.07 - RJS - Star formation
17.07 - RJS - Supernovae and winds
24.07 - **EXAM**

Exercises

- 02.05, 16.05, 23.05, 06.06, 13.06, 20.06, 27.06, 04.07, 11.07, 18.07
- NO exercise sessions on 18.04, 25.04, 09.05, 30.05
- Ten assignments in total, each worth same number of points

Suggested reading

Textbooks

- "*The Physics and Chemistry of the Interstellar Medium*", A. G.G.M. Tielens, 2005, Cambridge University Press
- "*Physics of the Interstellar and Intergalactic Medium*", B. T. Draine, 2010, Princeton University Press

Review articles

- "*The interstellar environment of our galaxy*", K. M. Ferriere, 2001, Rev. Mod. Phys., 73, 1031
- "*Control of star formation by supersonic turbulence*", M.-M. Mac Low & R.S. Klessen, 2004, Rev. Mod. Phys., 76, 125
- "*Theory of Star Formation*", C. McKee & E. Ostriker, 2007, ARA&A, 45, 565

Any Questions?

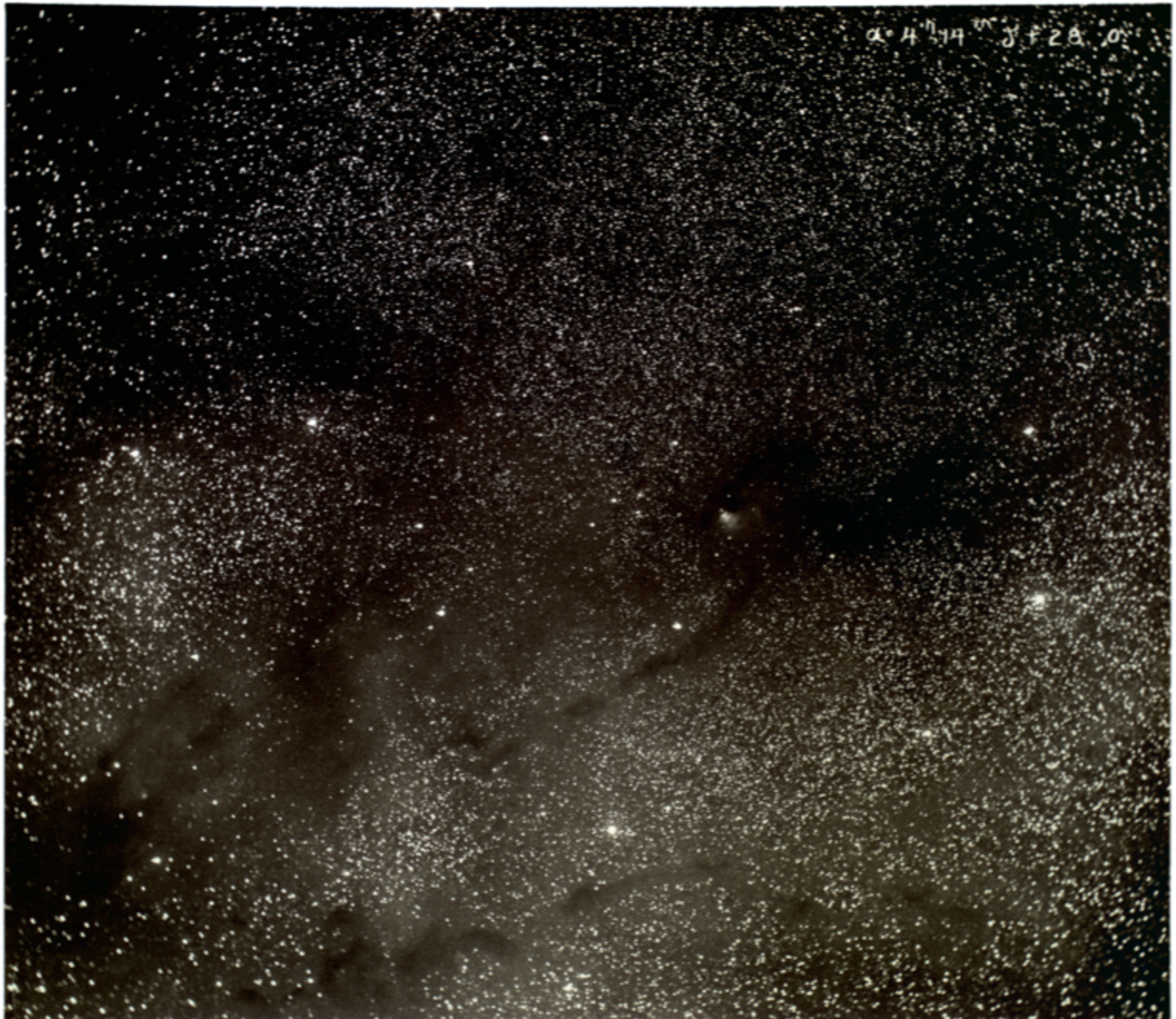
How do we know there is an ISM?

- Our story starts c. 1800 with William Herschel
  - Herschel catalogued bright patches of the sky, termed "nebulae"
  - Many of these nebulae were actually galaxies, but some were gas clouds within the Milky Way

- 1860s: Huggins showed that some nebulae (e.g. Orion) have pure emission spectra, like a gas, while others (e.g. Andromeda) have star-like spectra

- 1904: Hartmann observations of delta Orionis
  - Ca II K lines did not show periodic velocity shift associated with binary system
  - These lines also very weak, very narrow
  - Hartmann concluded that they were due to intervening absorption from gas between the binary and Earth
  - First direct observation of ISM to be recognized as such

- 1919: Barnard's catalog of dark clouds
  - many dark patches in plane of Milky Way
  - Barnard argued that although some of these may be due to absence of stars, most of them must be foreground clouds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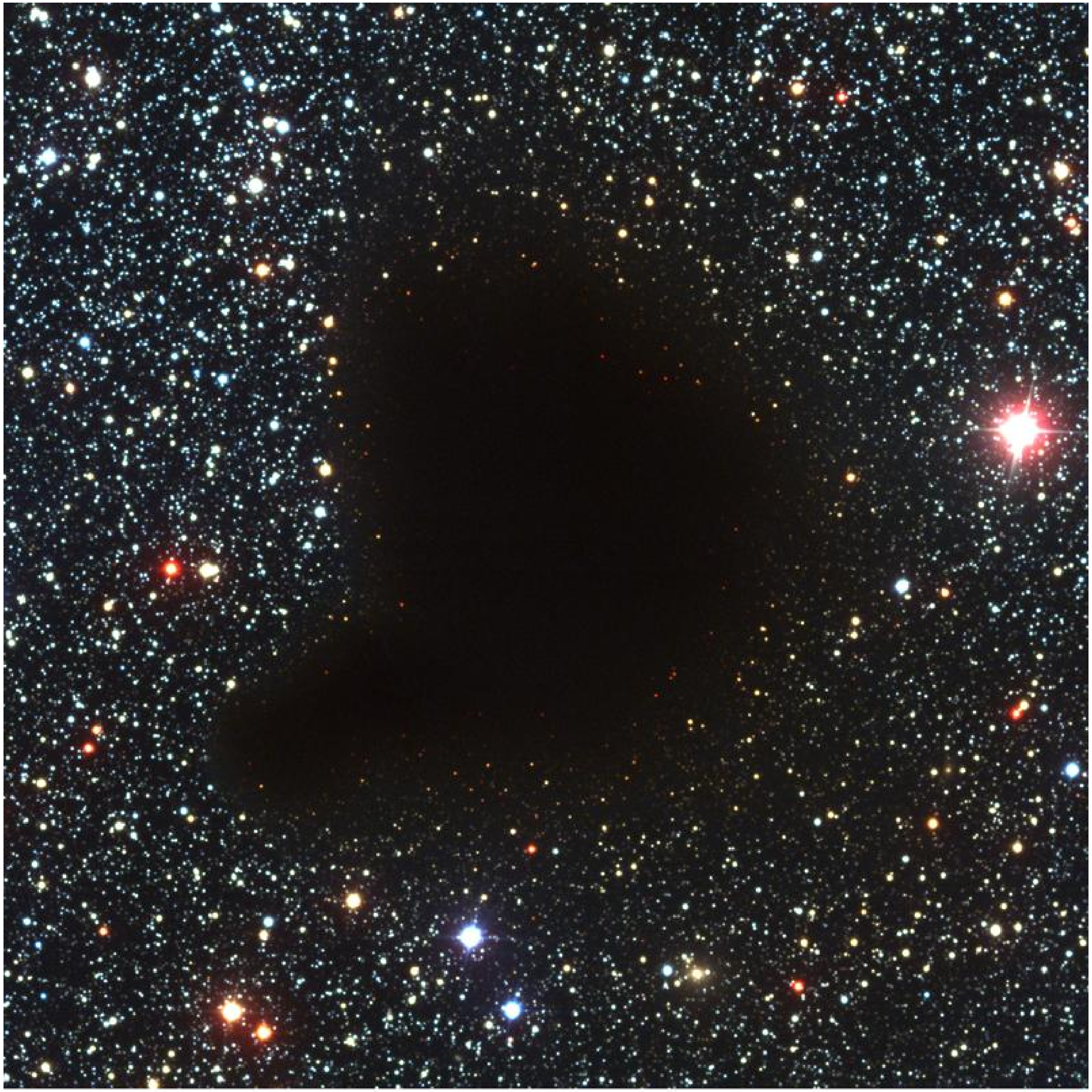


The "Black Cloud" B68
(VLT ANTU + FORS1)

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

- 1930: Trumpler found that luminosity distances and angular diameter distances of Galactic star clusters showed systematic differences
    - Luminosity distance always larger than angular diameter distance
    - Discrepancy grows as angular diameter distance increases
    - Explanation: intervening **extinction** makes clusters fainter, hence luminosity distance overestimated

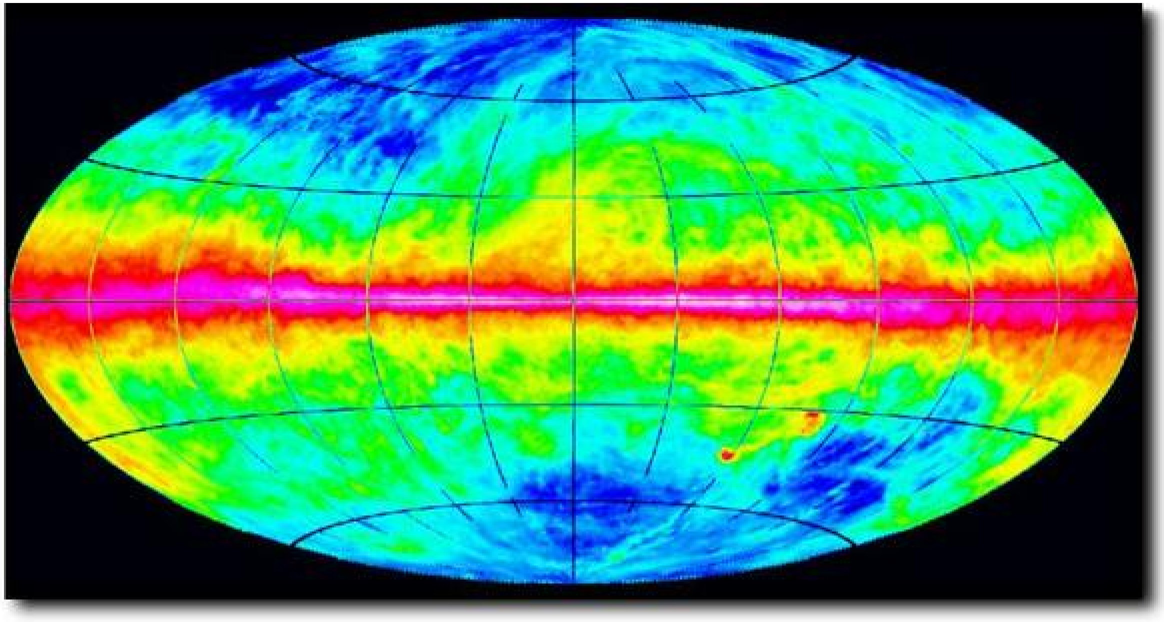
- 1937: Struve showed that strength of Ca II K feature grows with increasing distance
    - Again consistent with this feature being due to gas between us and the stars

- 1937-1940: First optical observations of small interstellar molecules (CH, CH^+, CN)
  - Seen in absorption in high-resolution stellar spectra
  - Narrow line-widths imply that they don't come from the stellar atmosphere

- 1945: van de Hulst predicts existence of 21 cm hyperfine line of atomic hydrogen
  - He did this while still a graduate student!

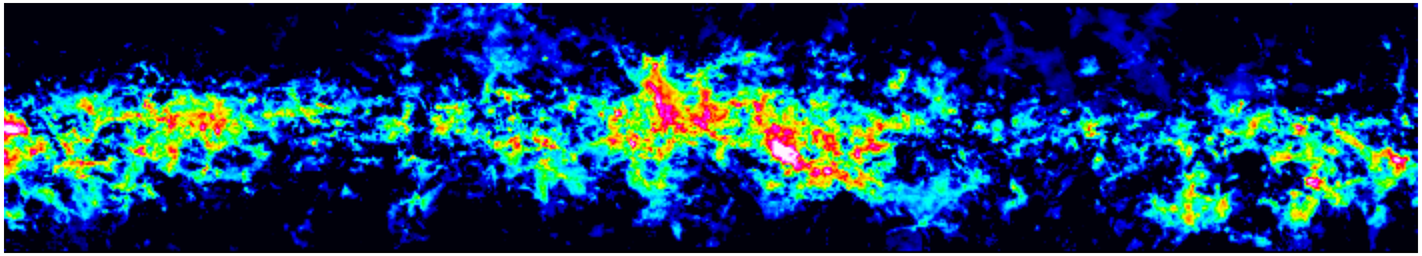
- 1951: Ewan & Purcell make first successful detection of Galactic 21 cm emission
  - Allowed ISM to be studied in emission, rather than just absorption

- 1950s-1960s: subsequent 21cm work showed that atomic hydrogen is a major part of the Galactic disk
    - Total HI mass around 5 billion solar masses
    - Accounts for 10% of disk mass



- 1968: First polyatomic molecule detected (NH_3)

- 1970: First detection of 2.6 mm line of CO
  - As we will see in later lectures, very difficult to detect molecular hydrogen in ISM
  - CO reasonably good tracer of molecular regions, so detection of CO allowed molecular phase to be studied in detail for first time
  - Subsequent observations showed that most molecular gas found in large clouds (Giant Molecular Clouds or GMCs), total molecular mass around one billion solar masses

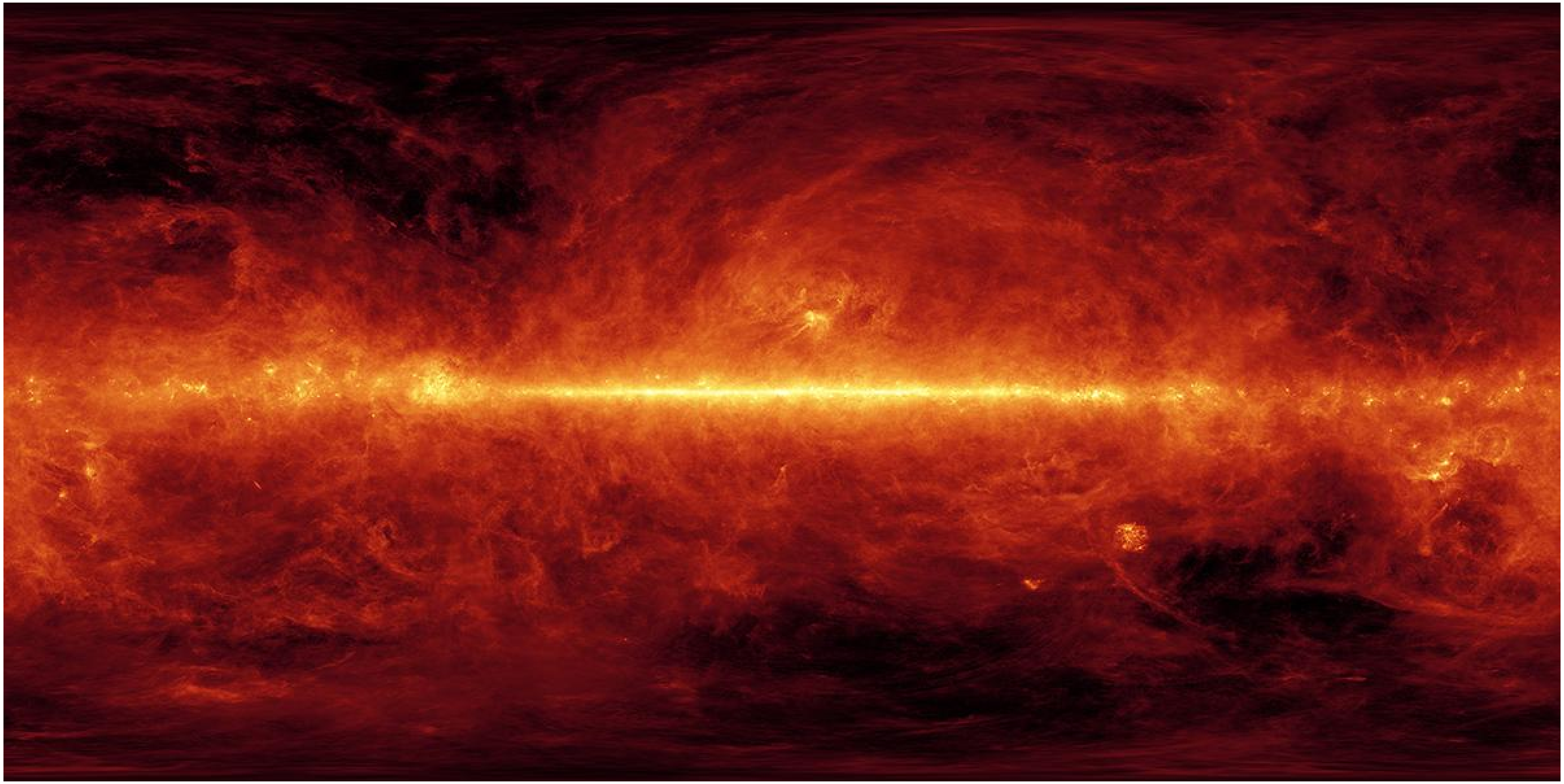


- 1960s, 1970s: first X-ray telescopes in space
  - Large amounts of diffuse soft X-ray emission
  - Too soft to be from extragalactic sources, must have local origin
  - Evidence for large amounts of hot gas ($T \sim 10^6$ K)

- 1973: Copernicus satellite measures UV spectra of nearby stars
  - Allows interstellar H_2 to be studied in absorption
  - Followed up by FUSE in 2000

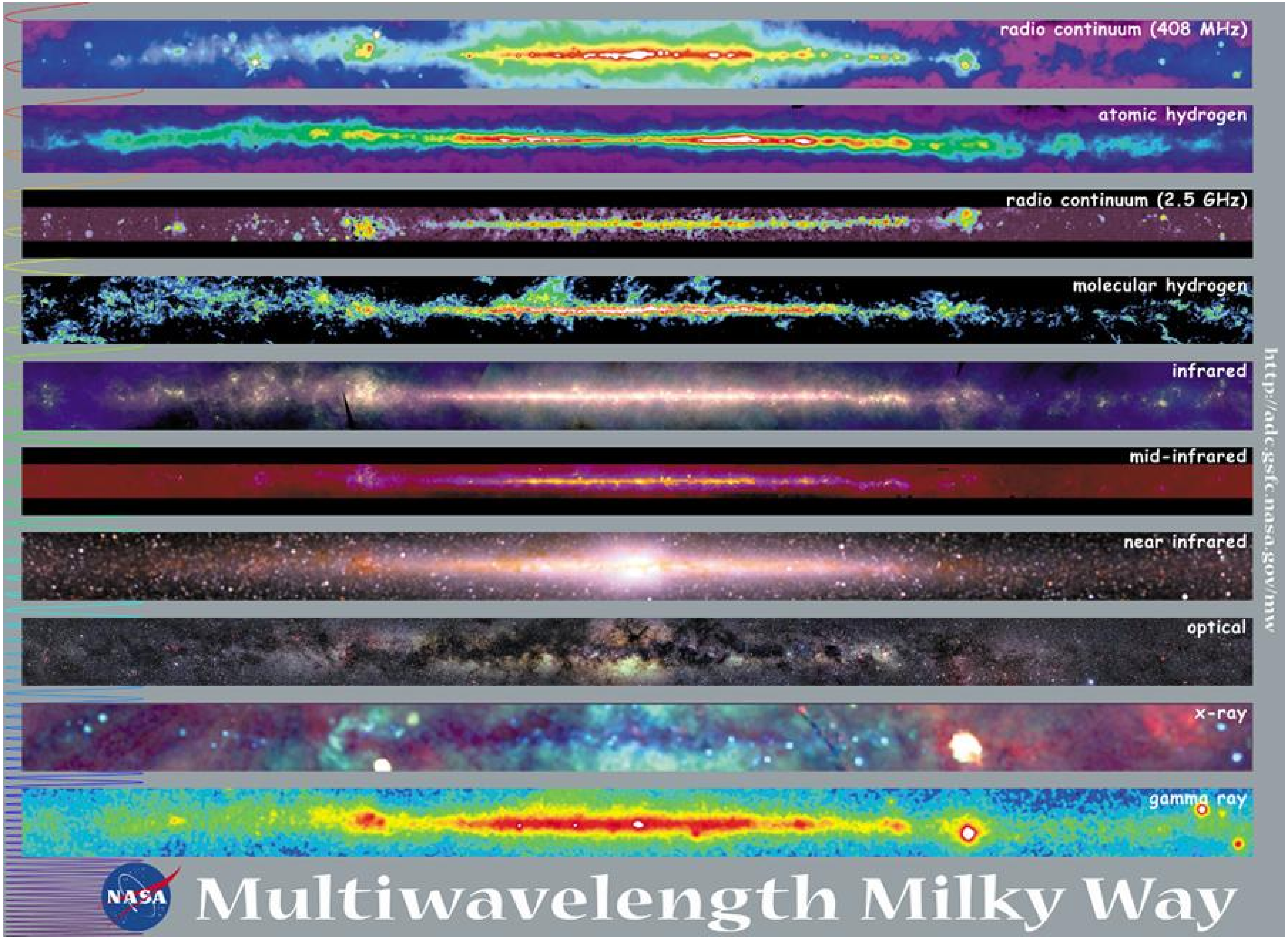
- 1983: IRAS satellite conducts all-sky survey at 12, 25, 60 and 100 microns
    - First truly large-scale IR view of the ISM
    - Detected copious emission from warm dust
    - First of long series of space-based IR telescopes, followed up by ISO, Spitzer and now Herschel

- Now: boom time for sub-mm and mm astrophysics
    - Herschel has been a great success and analyzing Herschel data will keep people busy for a long time to come
    - SOFIA is ramping up to full operations
    - ALMA is complete and will also be fully operational in a few years time



IRAS All-Sky image at 100 microns

Herschel Hi-Gal image of part of galactic plane


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

Components of the ISM

- Dust
  - Small solid particles, largely graphite or silicates ("soot" and "sand"), plus some ices and organics
  - Responsible for interstellar extinction, most IR emission
  - Extinction measurements at different wavelengths allow one to constrain size distribution, show that most grains are small (< 1 micron)
  - Total mass in dust is ~1% of ISM mass, roughly 50% of "metals" (i.e. elements heavier than He)

- Cosmic rays
    - Highly energetic charged particles (electrons, protons, plus heavier nuclei)
    - Power-law velocity dispersion; **non-Maxwellian**
    - Highest energy CRs extragalactic, but most come from Galactic sources (especially supernovae)
    - Negligible contribution to total ISM mass, but substantial energy density

- Photons
    - Cosmic microwave background
    - Starlight
    - Thermal emission from dust, hot gas
    - Synchrotron emission from relativistic electrons
    - Line emission from gas

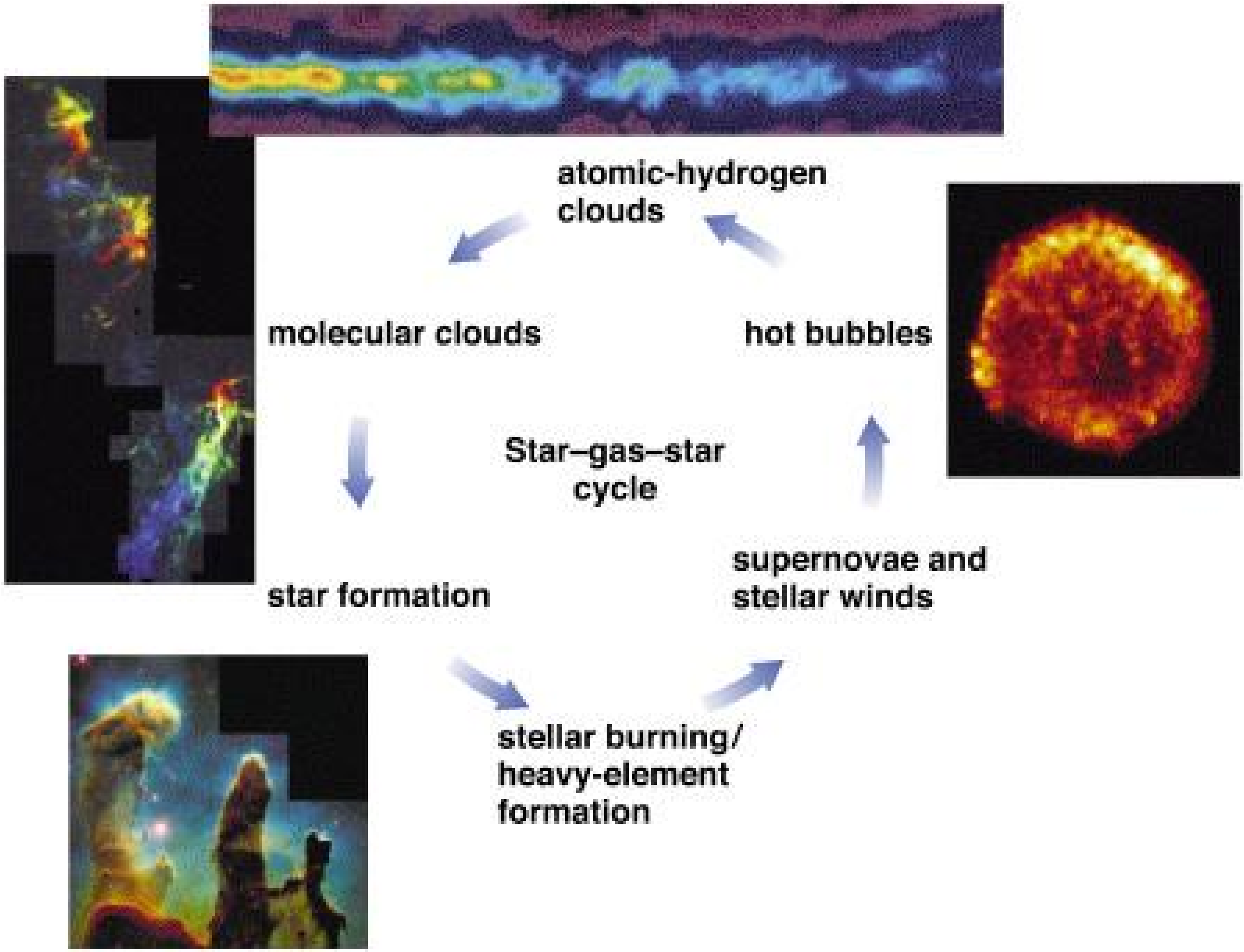
- Magnetic fields
  - Much of ISM is ionized, but total charge is neutral and charge separation rarely occurs
  - Electric fields are therefore unimportant
  - Magnetic fields do exist, and play important role in gas dynamics
  - Information on magnetic field strength, geometry etc. comes primarily from two sources
    1. Polarization measurements - dust grains become aligned with magnetic fields and hence light interacting with dust becomes polarized
    2. Zeeman effect in dense molecular gas
  - Considerable energy stored in magnetic field

- Gas
  - Multiple different "phases" (although how well-separated these phases actually are is an interesting open question)
  - Hot ionized medium (HIM)
    - Diffuse ($n < 0.01\ cm^{-3}$), high temperature ($T > 10^6$ K)
    - Highly ionized
  - Warm ionized medium (WIM)
    - $T \sim 10^4$ K, density depends on environment
    - Primarily found in HII regions around massive stars
  - Warm neutral medium (WNM)
    - $T \sim 6000$ K, $n \sim 0.3\ cm^{-3}$
  - Cold neutral medium (CNM)
    - $T \sim 60$ K, $n \sim 30\ cm^{-3}$
  - Molecular gas
    - $T \sim 10\text{-}20$ K, $n > 100\ cm^{-3}$

- ISM has very high Reynolds number, gas is generally turbulent
  - HIM: subsonic
  - WIM, WNM: transonic (i.e. Mach number ~ 1)
  - CNM, molecular: supersonic

- Total turbulent KE > total thermal energy

- Phases not fixed - constant cycling of matter from one to another


atomic-hydrogen clouds
molecular clouds
hot bubbles
Star–gas–star cycle
star formation
supernovae and stellar winds
stellar burning/ heavy-element formation

- Also important to remember that Milky Way is not a closed system
    - Continuing inflow of gas from IGM, may power turbulence in outer disk
    - Outflow of gas from disk into halo or even into IGM also possible (although doesn't appear to be going on right now)

Summary

- ISM is a complex, multi-component system
- In this lecture course we will take a reductionist approach to understanding it - start by studying small-scale microphysics and then look at how it all fits together
- Since so much of what we know about the ISM comes from studying emission or absorption lines of the gas, we start next week by looking at the physics of this process