V838 Mon Light Echo illuminating the 3-D structure of the ISM

The Interstellar Medium

Not Quite Empty Space

- Excellent vacuum by terrestrial standards
- gas, dust, molecules and dark matter
- starlight, cosmic rays
- magnetic fields,
- cycles of activity and quiescence driven by gravity, star formation episodes, supernova explosions galactic rotation
- shock waves

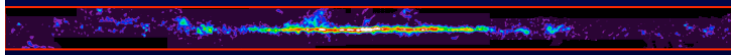
Why study the ISM?

- Profoundly alters our view of stars and galaxies
- Plays a key role in Star Formation
- Reservoir of gas, molecules and dust
- Continuous cycles of supply and replenishment with processed material
- Keys to the origin of complex species, leading to planets and life
- Need to understand the Galactic Foreground to extract the CMB – intensity and polarization
- Dark Matter?

The Interstellar Medium in our Galaxy

- From the Solar System to the edges of the Galaxy

- Galactic scale effects



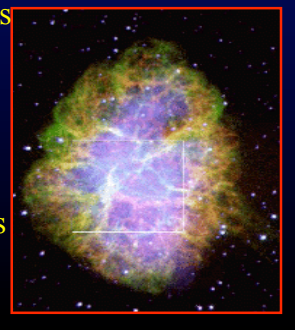
  - Dense clouds confined to Galactic Disk
  - High Velocity Clouds
  - Galactic Halo
  - Galactic Fountains
  - Abundance gradients
  - Spiral Structure

Large scale galactic winds

Driven by star-formation episodes, SN explosions or AGN

Constituents of the ISM

- Diffuse medium, primarily atomic rather than molecular, relatively transparent
- Molecular Clouds, cold molecular gas and dust opaque at optical wavelengths
- Enriched by Ejecta from evolved stars: Supernovae, Red Giants, Novae, Planetary Nebulae etc.
- Disrupted by energetic events - Supernovae

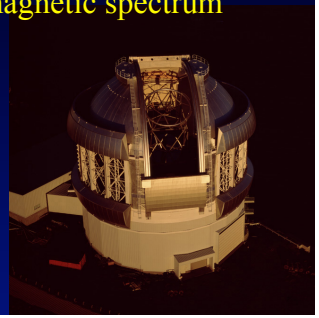


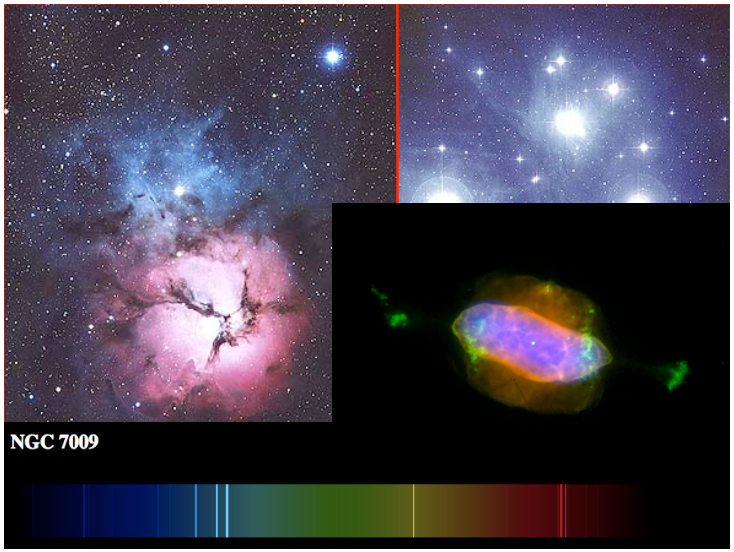
Phases of the ISM

- Hot Ionized - like local ISM $T \sim 10^6$ K comprises ~70% of volume, but little mass
- Warm Ionized - HII regions $T \sim 10^4$ K around OB stars small fraction by mass and volume
- Warm Atomic neutral material around denser clouds, $T \sim 10^3 - 5.10^3$ K, partially ionized, ~20% of volume, 21cm line
- Cool Atomic diffuse clouds: $T \sim 100$ K, few % of volume, but $n \sim 10^{7\text{-}8}$ /m^3 so significant mass
- Cold Molecular $T \sim 10\text{-}30$ K $n > 10^9$ m^3 <1% of volume but significant mass fraction in GMC

Probing the Interstellar Medium

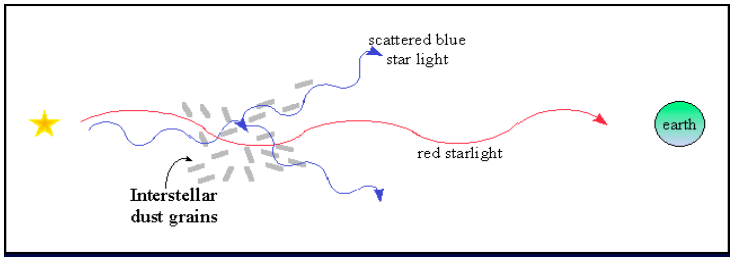
- Different techniques for different environments
- X-ray to Radio from Satellites and Ground
- Access to the whole electromagnetic spectrum
- Imaging, photometry, spectroscopy, polarimetry
- Separate circumstellar from true interstellar effects by comparing stars at different distances and along different sightlines





Composition of the ISM

- Assume cosmic elemental abundance values for the interstellar material
- Measure elements in the gas phase and infer missing material condensed into dust grains
- Interstellar atoms and molecules absorb light emitted by stars, absorption lines
- Reflection nebulae
- Emission nebulae excited by hot stars

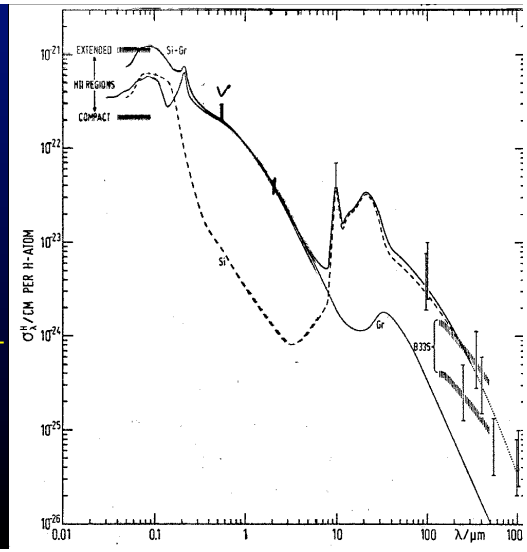


- Distant stars appear redder than nearby examples
- Attributed to scattering by small particles <λ - cosmic dust
- scattering efficiency falls with increasing wavelength and becomes unimportant in the thermal infrared where absorption dominates
- Extinction = scattering + absorption
- Structure in the extinction curve provides information on the dust particles

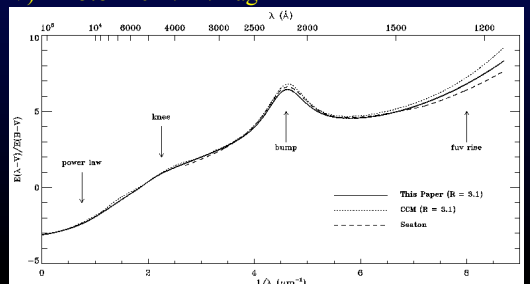
Interstellar Extinction Curve

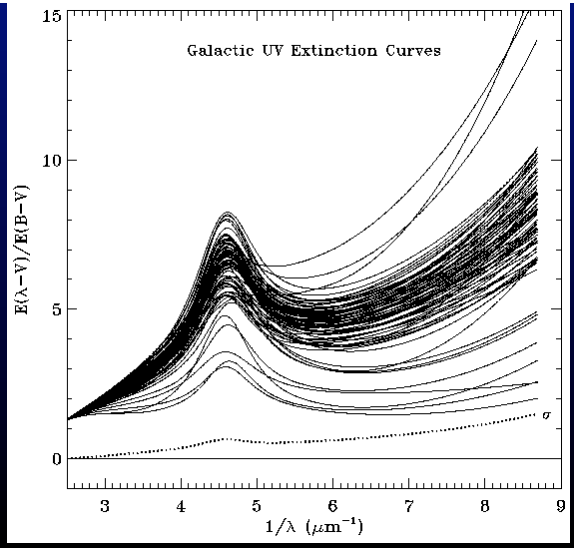
- Generally not possible to look at one object to cover the whole spectrum - need to patch together observations from UV to IR
- Different lines of sight reveal differences in detail Changing dust grain sizes and/or mixture of species, but overall shape is maintained
- Dust grains absorb starlight, heat up and emit at infrared wavelngths

- Rise towards short UV wavelengths due to tiny grains
- Peak near 220 nm - possibly due to carbon grains
- Decreases in IR - grains ~100nm
- Peaks near 10 and 20 µm attributed to silicates

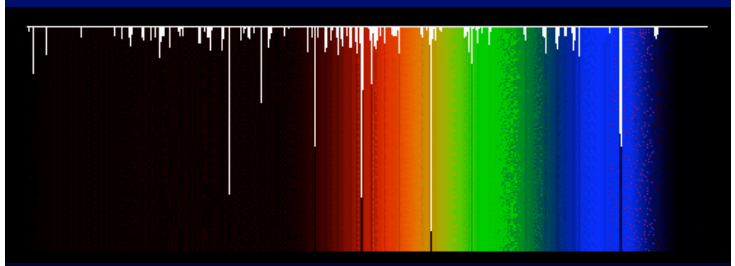


- Often given as E(B-V) or A(V)
- Standard curves, but beware of special regions (e.g. Orion)
- Often classed by R = A(v)/E(B-V) [~ 3.1] = ratio of selective to total extinction
- Smaller variations in the IR, but not well characterized $A(\lambda) \sim \lambda^{-1.8}$
- Substantial variations in the UV - changes in small grain populations
- N(H)/E(B-V) ~ 5.8x 10^{25} /m^2/mag





Diffuse Interstellar Bands



- > 100 weak absorption bands seen in the visible spectra of reddened stars, diffuse bands with $\delta\lambda \sim 8\text{-}30$ Å
- Associated with the Diffuse ISM, correlate with extinction
- Bands show evidence of molecular band shapes - large organic molecules?

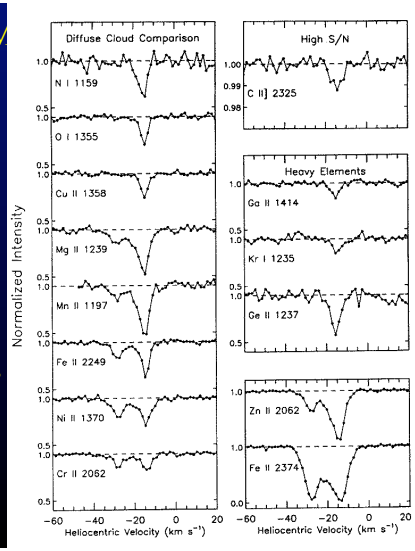
Probing the diffuse ISM at short wavelengths

Diffuse medium with low column densities best observed at short wavelengths

UV spectroscopy of hot bright stars - relatively local region (few hundred parcsec)

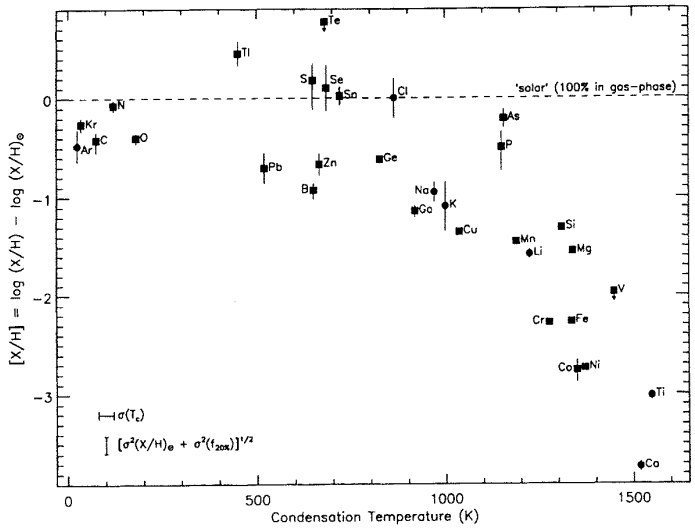
Interstellar absorption lines arise from atomic or ionic gas or molecules

Calculate amount of intervening material along the line of sight to stars



Probing the ISM
The diffuse ISM at short wavelengths

- High resolution spectroscopy from the ground and the Hubble Space Telescope:
  - These elements are presumably condensed into dust where the narrow atomic transitions are suppressed.
  - Degree of depletion correlates with condensation temperature
  - Places severe constraints on the composition of interstellar dust
  - Dominated by O, C, Si, Mg, Fe, Ca



The Local ISM

- Element Abundances (ppm wrt H)

Element	Gas	Dust	Total
– Oxygen	320	<180	450
– Carbon	140	100:	200
– Nitrogen	60	0	60
– Magnesium	5	<30	30
– Silicon	10	25	35
– Iron	5	30	35

- Observations of nearby stars reveal the ISM structure in the solar neighbourhood

The Local ISM

- The sun lies near the middle of a hot, soft X-ray emitting bubble of low density gas.
- Radius ~200pc near poles 30pc in plane
- $T \sim 10^6$ K, $n \sim 5.\ 10^3\ m^{-3}$ $N \sim 10^{14}$ H/cm^2
- Fully ionized, bounded by warm neutral gas
- Origin?
  - Recent local Supernova?,
  - Stellar Winds?
  - How typical of ISM?
- Very local ISM - Local cloud, r~ 3pc, partially ionized

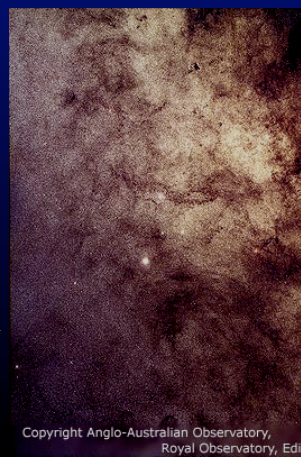
Probing the ISM
The diffuse ISM at longer wavelengths

- Diffuse medium with higher column densities best observed at infrared wavelengths
- IR spectra of cool bright stars - across the Galaxy
- Interstellar absorption lines and bands give columns of atomic or ionic gas, molecules & dust
  - Dust bands are broader and difficult to identify uniquely
  - tentative identifications based on depletions and matches with laboratory spectra
- Earth-based telescopes + ISO/Spitzer

The path to the Galactic Centre

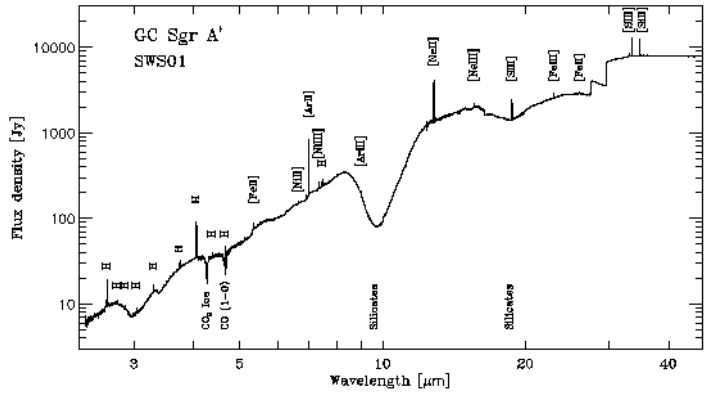
- ~8kpc path from the Earth to the Galactic Centre
- mostly through diffuse interstellar material, but with some molecular components near the centre.
- Evidence for a slow increase in heavy element abundance towards the GC

The Galactic Centre
30 magnitudes of visual extinction -
1 photon in 10^{12} to the Earth at 0.5 µm
1 photon in 30 makes it at 2 µm



Dust towards the Galactic Centre

- Absorption Bands at 3, 10 and 20 µm



Estimating Extinction

- compare well-understood Standard candles and establish effects of intervening medium
- Reddened stars
- Hydrogen emission line ratios
- Compare galaxies to templates etc.

Extinction in the Diffuse ISM

- UV – 220nm bump and short wavelength rise – quite variable
- Optical to Near-IR fairly linear, power law, less variable, DIBs, maximum of interstellar polarization curve
- Mid-IR: Silicate absorption bands at 10 and 20um. Polarized so (some) silicate grains are non-spherical and aligned
- Far-IR/submm Power law, but not really examined in detail.

- Large surveys are allowing a much more detailed look at IS extinction, and more variations are being seen. e.g Gosling et al 2009, Fitzpatrick & Massa 2009

Back to V838 Mon

Polarization measurements confirm that scattering off dust in the ISM is the mechanism producing the 'moving' light echo and allowing a distance estimate of 6.1kpc +/-10% from the geometry and timing of the echo

(Sparks et al 2008)

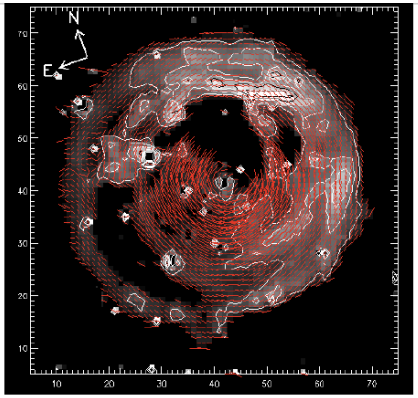


Figure 3. The echo image of 2002 December 17 (contours and greyscale image) with polarization electric vectors superimposed. The directions of the electric vectors are indicated by the red lines, whose lengths are proportional to the degree of polarization. The largest values are about 50%. Vectors are shown for every 30 pixels, and the polarization and position angles are the means and medians, respectively, averaged over 30 × 30-pixel boxes. This image has *not* been rotated to place north at the top, but instead remains in detector coordinates. Small tickmarks on the axes are separated by 1″.5. Note that the electric vectors are generally perpendicular to the direction to the central star, as expected for light scattered off dust particles.

pdf versions of these slides can be downloaded from my home page:

http://www-astro.physics.ox.ac.uk/~pfr/