The Interstellar Medium

Not Quite Empty Space

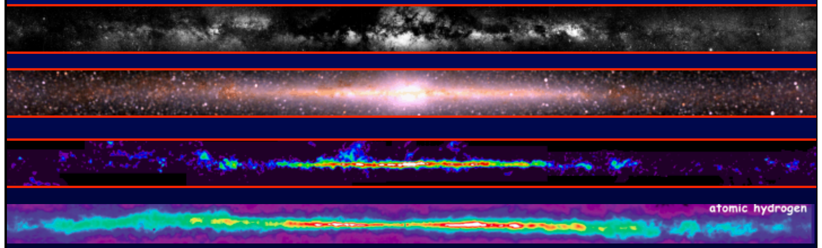
- Excellent vacuum by terrestrial standards
- gas, dust, molecules and dark matter
- starlight, cosmic rays
- magnetic fields,
- cycles of activity and quiescence
  driven by gravity, star formation episodes,
  supernova explosions galactic rotation
- shock waves

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
  - contains ~15% of the baryonic mass of the Galaxy
- 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

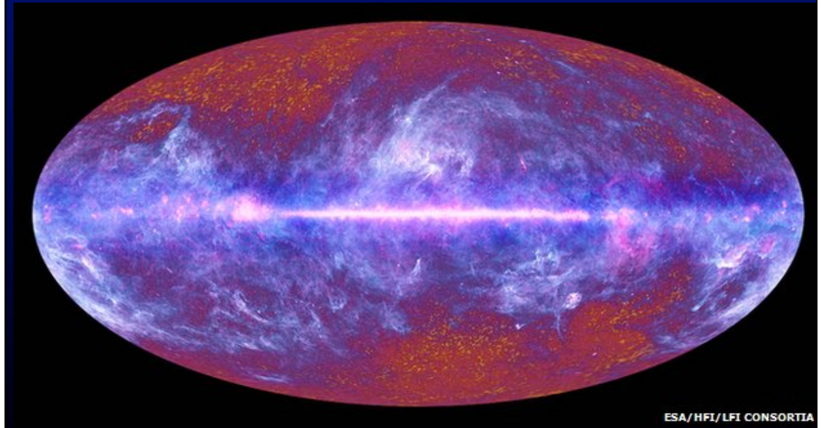
From the Solar System to the edges of the Galaxy



Galactic scale effects :

- Abundance gradients & Spiral Structure
- Dense clouds confined to Galactic Disk
- High Velocity Clouds
- [illegible]

Galactic Foregrounds



Need to know intensity and polarization of Galactic Foreground emission to reveal CMB in e.g. Planck data

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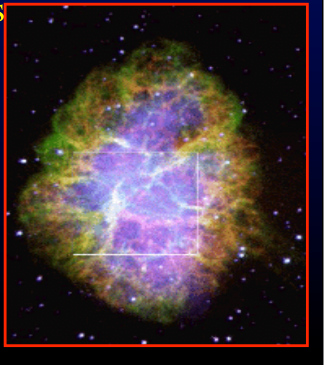
Large scale galactic winds

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

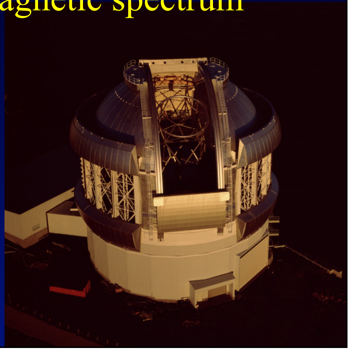


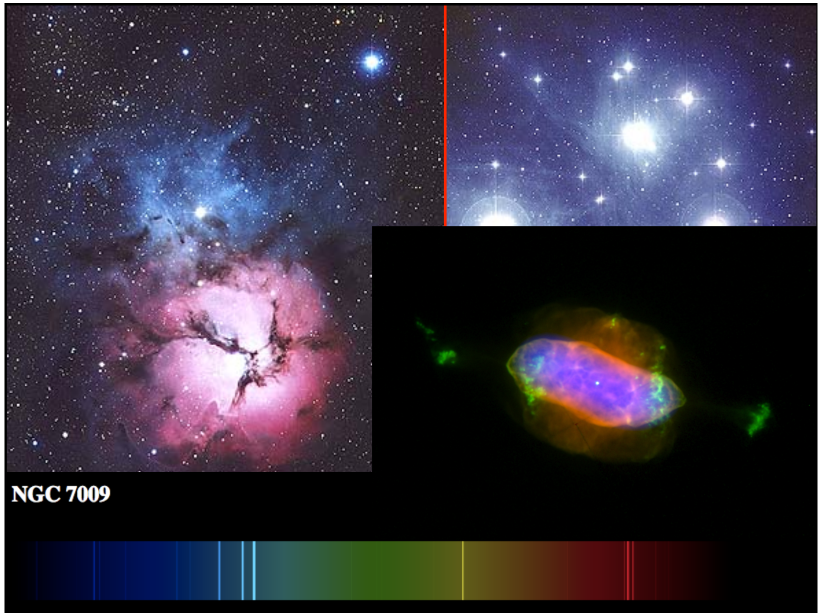
Phases of the ISM

- 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 $n \sim 10^{7-8} /m^3$ 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

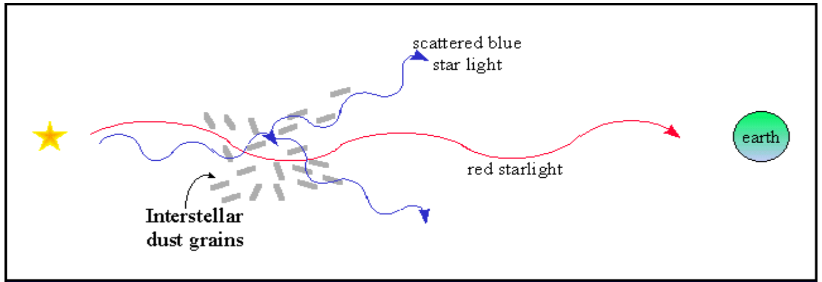
- Different techniques for different environments
- X-ray to Radio from Satellites and Ground
- Access to the whole electromagnetic spectrum
- Imaging, photometry, spectroscopy, polarimetry
- Separate circumstellar from true interstellar effects by comparing stars at different distances and along different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

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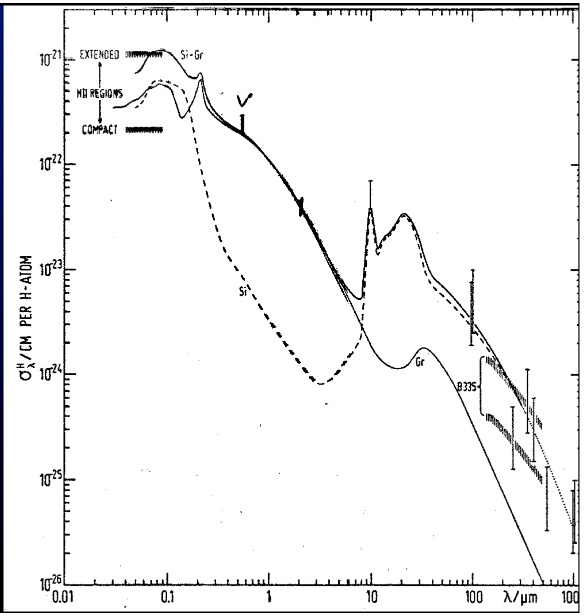
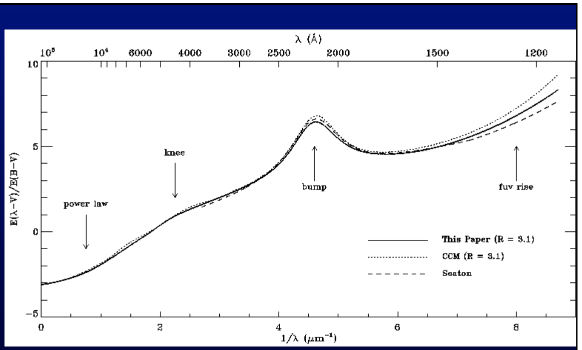
- Rise towards short UV wavelengths due to tiny grains
- Peak near 220 nm - possibly due to carbon grains
- Decreases in IR - grains ~100nm
- Peaks near 10 and 20 μm attributed to silicates



Standard Extinction curves are often used, but beware of special regions (e.g. Orion)

The extinction is often expressed in magnitudes, A(V) the total extinction in the V band



And characterised by R = A(v)/E(B-V) [~ 3.1] = ratio of total to selective extinction

Substantial variations in the UV, but smaller variations in the IR, though not as well characterized A(λ) ~ $\lambda^{-1.8}$

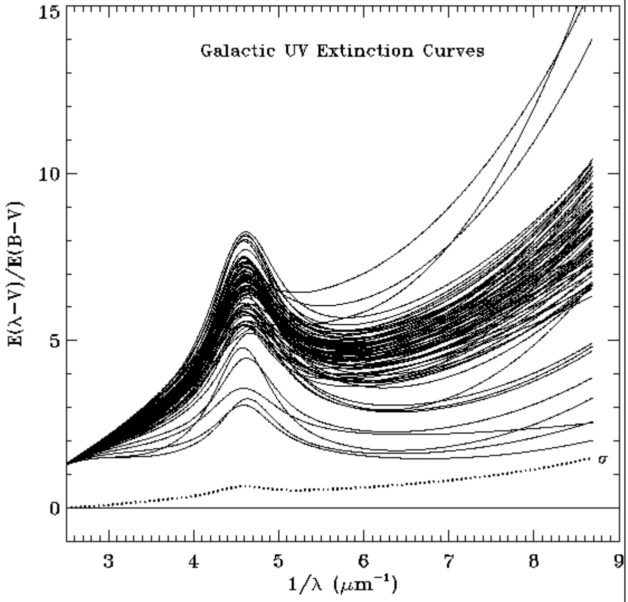
Substantial variations in the UV - changes in small grain populations

N(H)/E(B-V) ~ 5.8x 10^{25} /m^2/mag

Extinction Curve variations

Pronounced variations in UV rise and 220nm bump strength

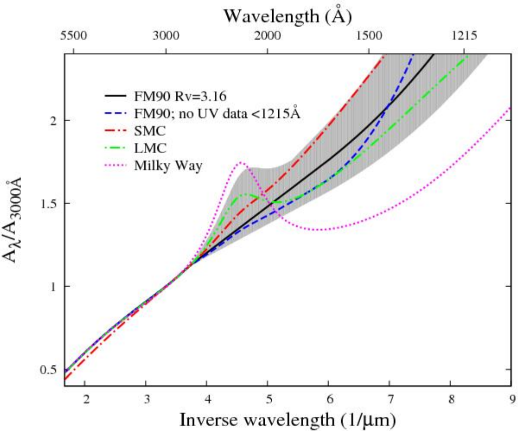
SMC has a very weak 220nm bump



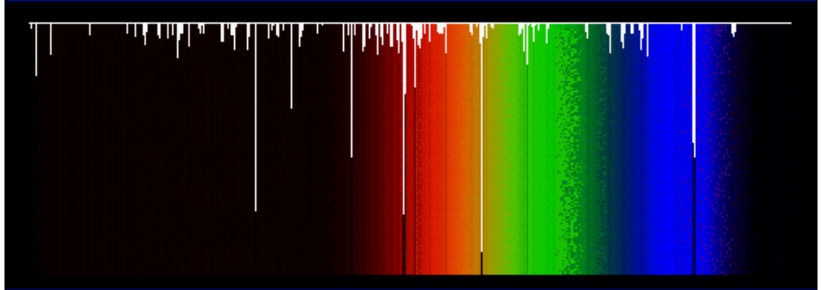
GRB extinction z=0.7 to 3.1

(Schady et al 2012 A&A 537)

GRB afterglows have weaker 220nm bumps than Milky Way sightlines (pink dotted) but are consistent with LMC and SMC extinction curves.



Diffuse Interstellar Bands



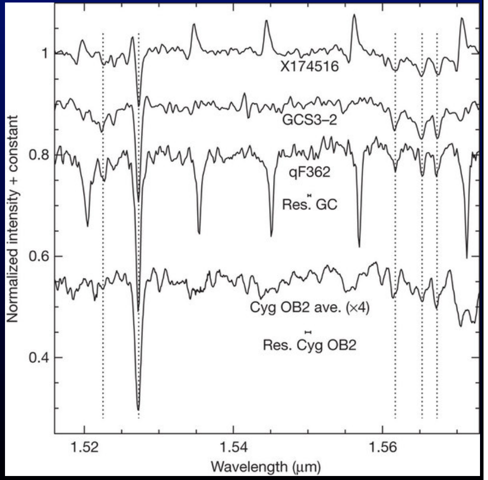
- > 100 weak absorption bands seen in the visible spectra of reddened stars, diffuse bands with δλ ~ 8-30 Å
- Associated with the Diffuse ISM, correlate with extinction
- Bands show evidence of molecular band shapes - large organic molecules?

New IR Diffuse Interstellar bands

Geballe et al 2011, have identified 13 more dibs in the H-band towards objects near the Galactic Centre (Nature 479,200).

More than 500 DIBs are now known , but so far none has a secure identification

One of the longest standing mysteries in Astronomy



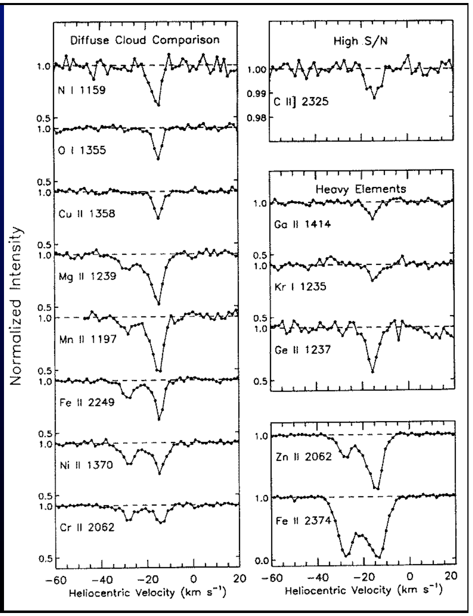
Probing the diffuse ISM at short wavelengths

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

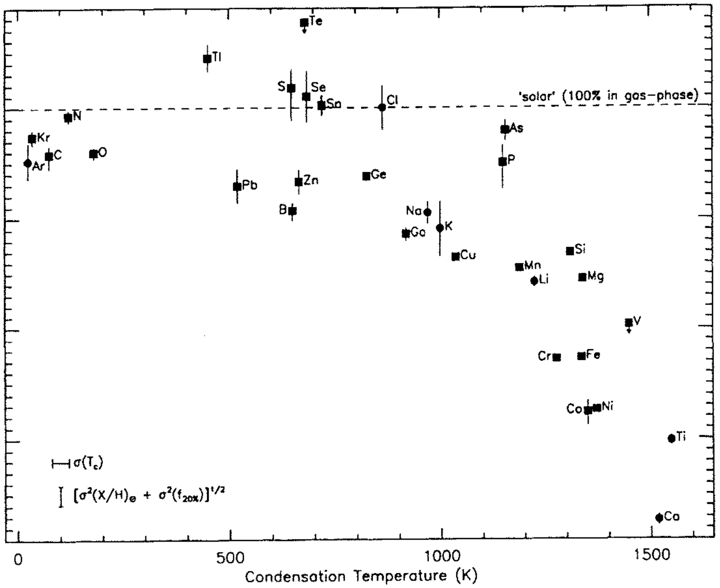
Calculate amount of intervening material along the line of sight to stars



Probing the diffuse ISM at short wavelengths

High resolution spectroscopy from the ground and the Hubble Space Telescope:

- Compare absorption depths with expectations from cosmic abundance
- 'Missing' 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

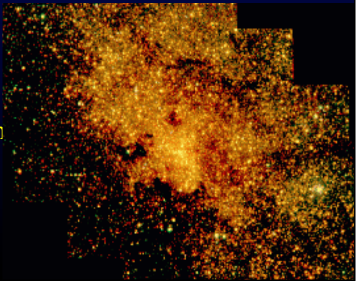
The Local ISM

- 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 ~ 10^6 K, n ~ 5. 10^3 m^{-3} N~ 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 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

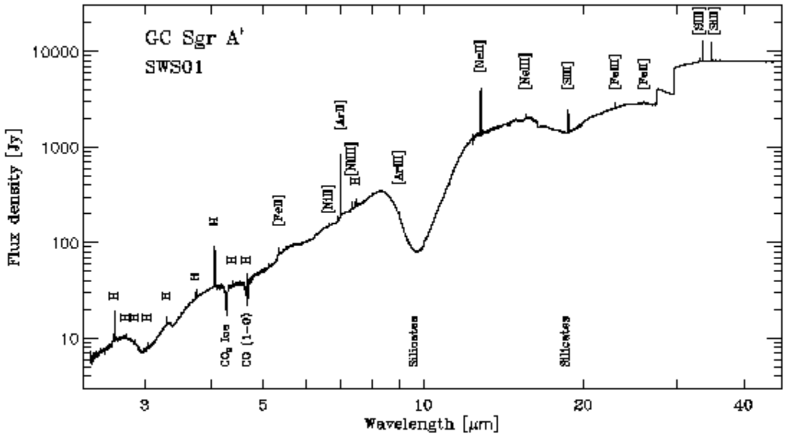


- ~8kpc path from the Earth to the Galactic Centre
- mostly through diffuse interstellar material, but with some molecular components near the centre.
- Evidence for a slow increase in heavy element abundance towards the GC

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



Galactic Centre extinction from HII recombination lines

The Astrophysical Journal, 737:73 (21pp), 2011 August 20 Fritz et al.

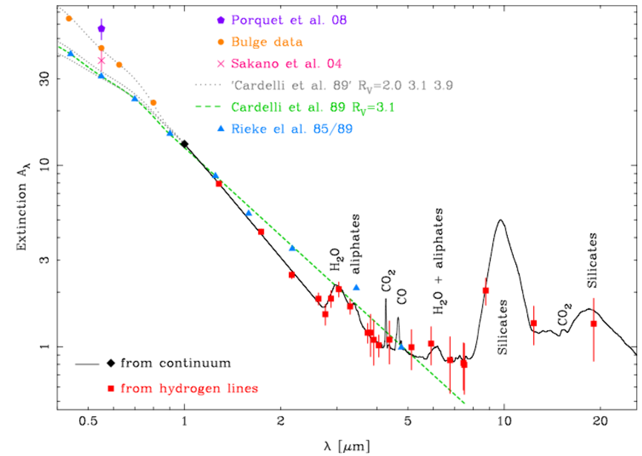


Figure 8. Extinction toward the central 14″ × 20″ of the GC. We use hydrogen lines for obtaining the extinction between 1.28 and 18 μm (red boxes) and stellar colors for 1 μm (black diamond). We interpolate the data by use of the continuum emission (black line). The spectral resolution of the interpolation is not high enough

Note: the sightline to the Galaxctic centre has enhanced silicate absorption by 2x compared to the solar neighbourhood (Roche & Aitken 1985)

Extinction correction of the GC

The Astrophysical Journal, 737:73 (21pp), 2011 August 20 Fritz et al.

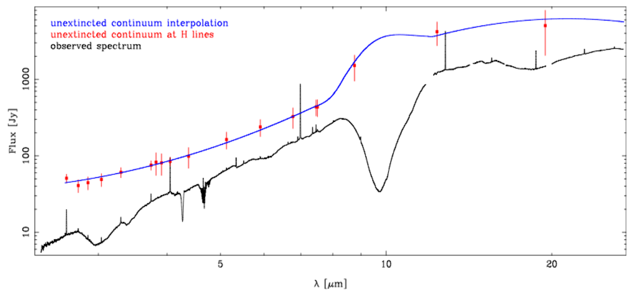


Figure 10. Measured and unextincted MIR continuum toward the GC. The black line is the observed ISO-SWS spectrum. We unextinct the continuum around the hydrogen lines by the hydrogen line extinctions there (red boxes). We interpolate these points to obtain the unextincted continuum (blue line).

Application of the extinction curve from Fritz et al (2011) reveals the intrinsic emission of the GC minispiral.

Estimating Extinction

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

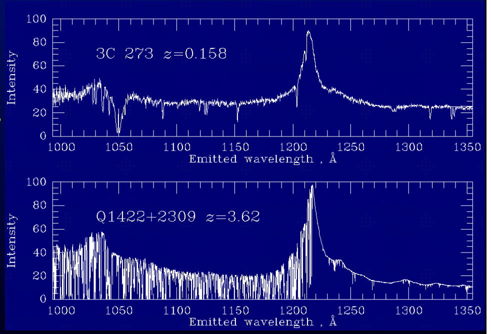
Extinction in the Diffuse ISM

- 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.

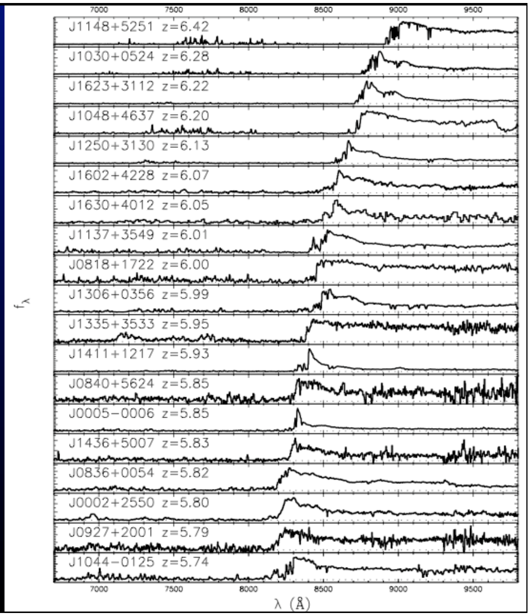
- Large surveys are allowing a much more detailed look at IS extinction, and more variations are being seen. e.g Gosling et al 2009, Fitzpatrick & Massa 2009

Intergalactic Medium

- Probed through absorption lines – element abundances and column densities
- Lyman alpha forest
- Damped (large optical depths) systems
- Deuterium abundance
- Evolution with redshift



Quasar spectra used to investigate where the IGM becomes neutral and hence opaque in the UV (Fan et al)



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)

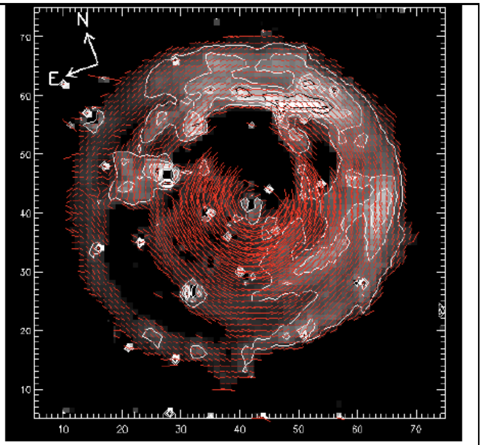


Figure 3. The echo image of 2002 December 17 (contours and greyscale image) with polarization electric vectors superimposed. The directions of the electric vectors are indicated by the red lines, whose lengths are proportional to the degree of polarization. The largest values are about 50%. Vectors are 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.

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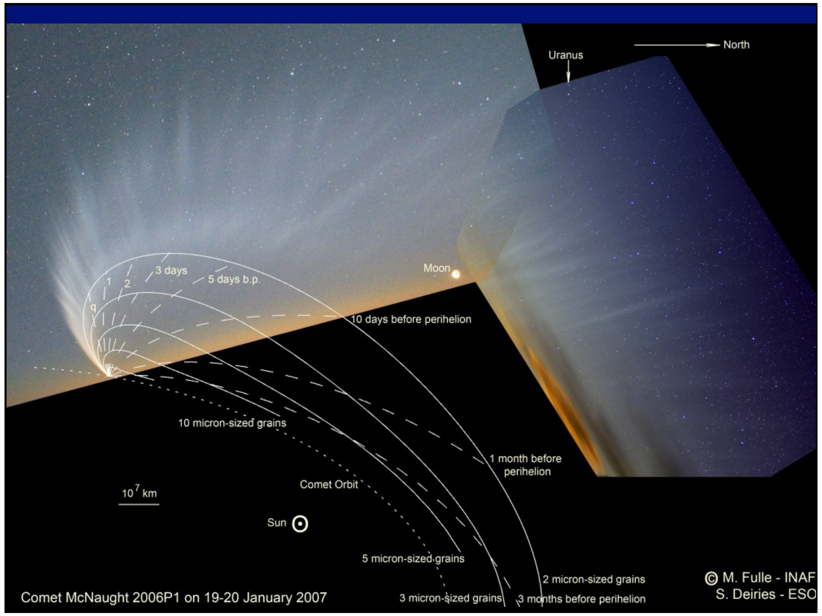
pdf versions of these slides can be downloaded from my home page:

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



Comet McNaught 2006P1 on 19-20 January 2007

Dense Interstellar Medium

- Molecular clouds
- Cold material, with temperature gradients
- Star-formation regions
- Dust that absorbs short-wavelength light re-radiates it at IR-Submm wavelengths

Dust Masses

- Thermal emission peaks at 50-200μm
  - R-J tail relatively insensitive to T_{dust} so gives reasonable estimate of M_{dust} - providing opacity known
- $M_{dust} = S_\nu D^2 / \kappa_\nu B(\nu,T)$
  - where S_ν is the flux density, κ_ν is the mass absorption coefficient [e.g. Hildebrand 1983]
  - Fits typically invoke a spectral index for the opacity, and one or two temperature components,
  - can have significant optical depths at $\lambda < 60\mu m$ and may have to consider non-thermal contributions from very small grains
  - could be significant dust mass hidden in cold component
  - At long wavelengths, may need to correct for synchrotron or free-free emission and for molecular emission

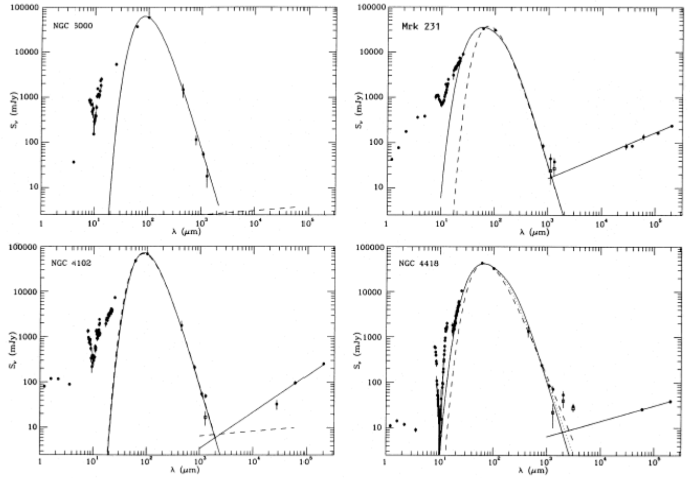


Figure 1. Infrared-to-radio emission from the target galaxies. The near- and mid-infrared photometry and spectroscopy are from Roche et al. (1991), except for the near-infrared photometry of Mrk 231 which is taken from Rieke (1976) and the 4.1-μm datum for NGC 6000 which is the continuum level reported by DePoy (1987). The 12–100 μm photometric points are taken from the *IRAS* Point Source Catalog, while the 450 μm–2 mm photometry is from the present work. The radio points are taken from Condon et al. (1990), Eales et al. (1990), Gioia et al. (1982) and Kojoian et al. (1976). The solid lines through the far-infrared and submillimetre data represent emission from isothermal dust grains, with ν^2 emissivity functions, and source sizes equated to the radio core sizes. These have dust temperatures of 38, 75 and 85 K and diameters of 3, 0.5 and 0.4 arcsec for NGC 4102, NGC 4418 and Mrk 231 respectively. Dashed lines represent emission from optically thin dust with $\beta = 2.0$ at temperatures of 34 K in NGC 4102 and NGC 6000 and 38 K in Mrk 231, and with $\beta = 1.0$ at 55 K in NGC 4418. The dotted line in NGC 4418 represents emission from a 78-K source of 0.5-arcsec diameter with $\beta = 1.5$. The dashed and solid straight lines longwards of 1 mm represent thermal and non-thermal radio components. Open squares indicate the level of excess emission above the dust component for Mrk 231, NGC 4102 and NGC 4418.

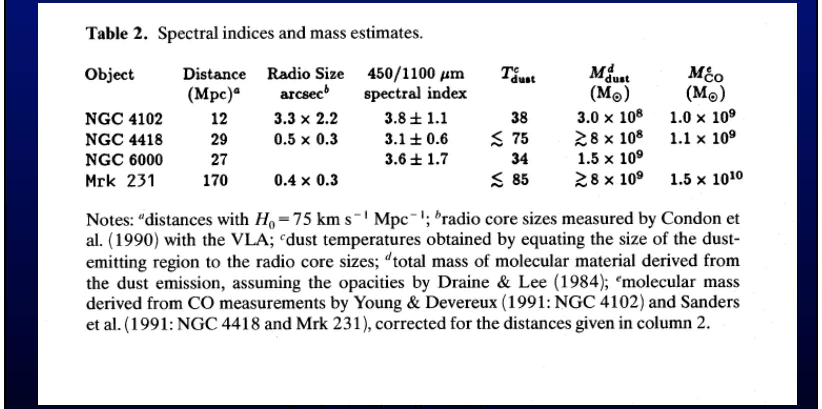


Table 2. Spectral indices and mass estimates.

Object	Distance (Mpc)[a]	Radio Size arcsec[b]	450/1100 μm spectral index	T^c_{dust}	M^d_{dust} ($M_\odot$)	M^e_{CO} ($M_\odot$)
NGC 4102	12	3.3 × 2.2	3.8 ± 1.1	38	3.0×10^8	1.0×10^9
NGC 4418	29	0.5 × 0.3	3.1 ± 0.6	$\lesssim 75$	$\gtrsim 8 \times 10^8$	1.1×10^9
NGC 6000	27		3.6 ± 1.7	34	1.5×10^9	
Mrk 231	170	0.4 × 0.3		$\lesssim 85$	$\gtrsim 8 \times 10^9$	1.5×10^{10}

Notes: [a]distances with $H_0 = 75$ km s^{-1} Mpc^{-1}; [b]radio core sizes measured by Condon et al. (1990) with the VLA; [c]dust temperatures obtained by equating the size of the dust-emitting region to the radio core sizes; [d]total mass of molecular material derived from the dust emission, assuming the opacities by Draine & Lee (1984); [e]molecular mass derived from CO measurements by Young & Devereux (1991: NGC 4102) and Sanders et al. (1991: NGC 4418 and Mrk 231), corrected for the distances given in column 2.

(Roche & Chandler 1993)

Note that there is degeneracy between Temperature and Spectral index. Recent work (Kelly et al 2012 : ApJ 752, 55) suggests that β depends on density : $\beta = 2.18 - 0.27 \times \log[N_{(H)}/10^{21}\ cm^{-2}]$ perhaps due to grain growth in dense regions

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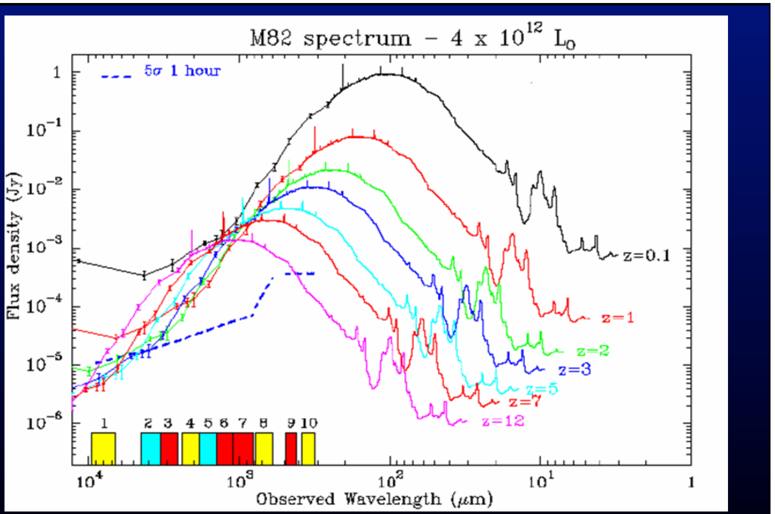


At ~1mm wavelength, star-forming galaxies at redshifts between 0 and 10 may have approximately constant flux as the dust emission peak shifts longwards. This is illustrated here where the spectrum of the nearby starburst galaxy M82 is redshifted out to z=12.

Anomalous cm wave emission

Excess emision above extrapolated radio flux at 20-40GHz

Attributed to small, rapidly-spinning grains radiating as dipoles (Lazarian & Draine 1998)

Coincides with dust emission regions

Spinning dust emission mechanism

assuming equipartition with rotational degrees of freedom:

$\frac{1}{2} I\,\omega^2 = \mathbf{kT}$.

Spherical grain, with $I = 2/5\ mR^2$, radius $R = N\ 10^{-10}$ m, and mass density = 1 kg m−3, the rotation frequency $=2\ 10^3\ \mathrm{Sqrt}(T/N^5)$ GHz

- T~100K, grain radius~100 atoms → ~50GHz

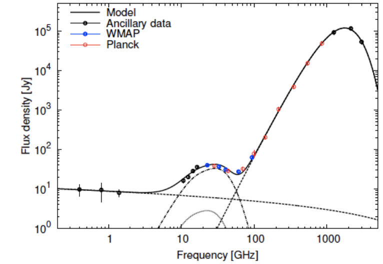


Fig. 4. Spectrum of G160.26-18.62 in the Perseus molecular cloud. The best-fitting model consisting of free-free, spinning dust, and thermal dust is shown. The spinning dust model consists of two components consisting of high density molecular gas (dot-dashed line) and low density atomic gas (dotted line).

Planck Collaboration - C Dickinson

Circumstellar Dust heated by stars

Starlight is absorbed by dust in circum-stellar environments.

The dust is heated and emits in the IR.

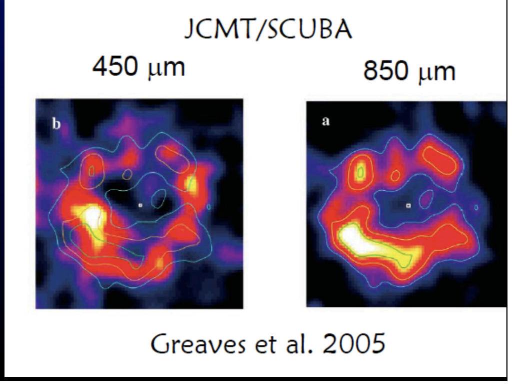
e.g. Eps Eri, a young nearby K star with a remnant 'debris' disk left over from its formation

Discovered at sub-mm wavelengths

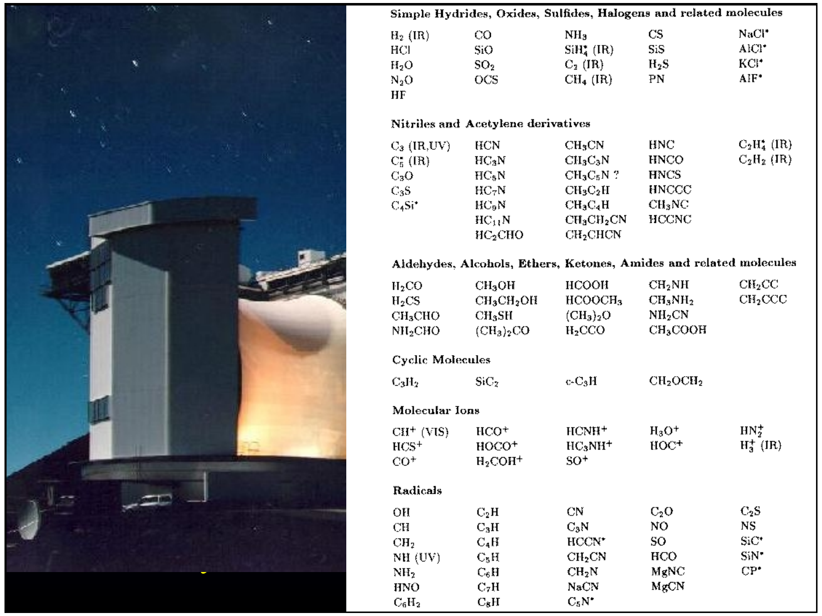
Sub-mm ring 35-80AU, T~20K

~0.03 M(Earth)

with warmer inner dust emission



Greaves et al. 2005



Simple Hydrides, Oxides, Sulfides, Halogens and related molecules

H_2 (IR)
HCl
H_2O
N_2O
HF
CO
SiO
SO_2
OCS
NH_3
SiH_4^* (IR)
C_2 (IR)
CH_4 (IR)
CS
SiS
H_2S
PN
NaCl*
AlCl*
KCl*
AlF*

Nitriles and Acetylene derivatives

C_3 (IR,UV)
C_5^* (IR)
C_3O
C_3S
C_4Si^*
HCN
HC_3N
HC_5N
HC_7N
HC_9N
$HC_{11}N$
HC_2CHO
CH_3CN
CH_3C_3N
CH_3C_5N ?
CH_3C_2H
CH_3C_4H
CH_3CH_2CN
CH_2CHCN
HNC
HNCO
HNCS
HNCCC
CH_3NC
HCCNC
$C_2H_4^*$ (IR)
C_2H_2 (IR)

Aldehydes, Alcohols, Ethers, Ketones, Amides and related molecules

H_2CO
H_2CS
CH_3CHO
NH_2CHO
CH_3OH
CH_3CH_2OH
CH_3SH
$(CH_3)_2CO$
HCOOH
$HCOOCH_3$
$(CH_3)_2O$
H_2CCO
CH_2NH
CH_3NH_2
NH_2CN
CH_3COOH
CH_2CC
CH_2CCC

Cyclic Molecules

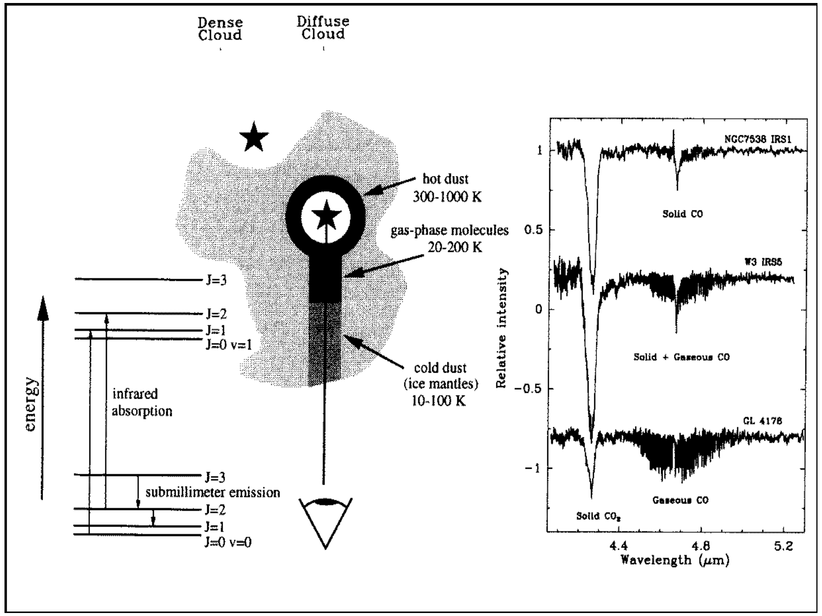
C_3H_2
SiC_2
c-C_3H
CH_2OCH_2

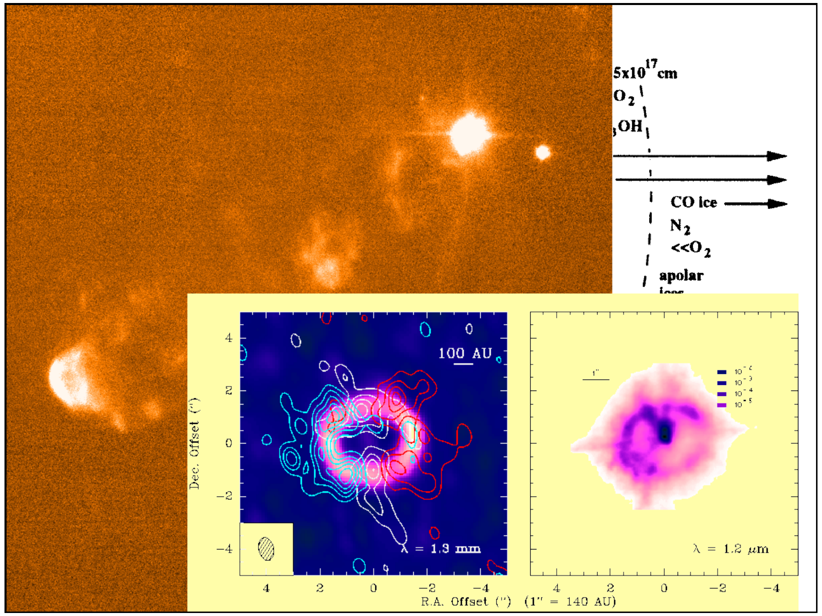
Molecular Ions

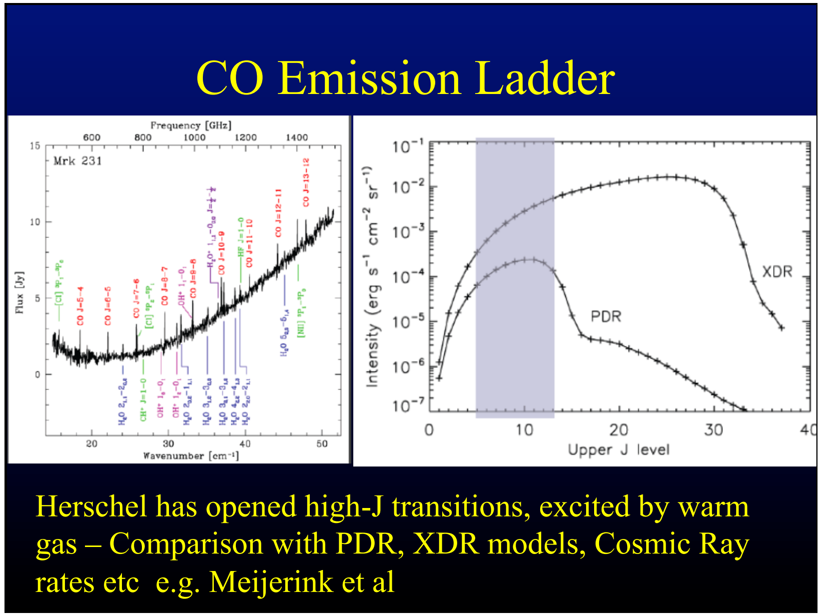
CH^+ (VIS)
HCS^+
CO^+
HCO^+
$HOCO^+$
H_2COH^+
$HCNH^+$
HC_3NH^+
SO^+
H_3O^+
HOC^+
HN_2^+
H_3^+ (IR)

Radicals

OH
CH
CH_2
NH (UV)
NH_2
HNO
C_6H_2
C_2H
C_3H
C_4H
C_5H
C_6H
C_7H
C_8H
CN
C_3N
HCCN*
CH_2CN
CH_2N
NaCN
C_5N^*
C_2O
NO
SO
HCO
MgNC
MgCN
C_2S
NS
SiC*
SiN*
CP*

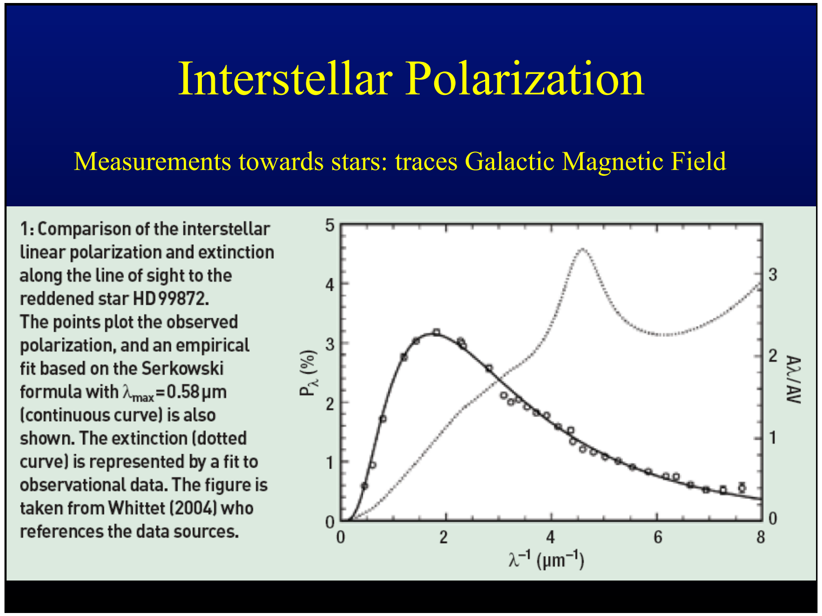






CO Emission Ladder

Herschel has opened high-J transitions, excited by warm gas – Comparison with PDR, XDR models, Cosmic Ray rates etc e.g. Meijerink et al



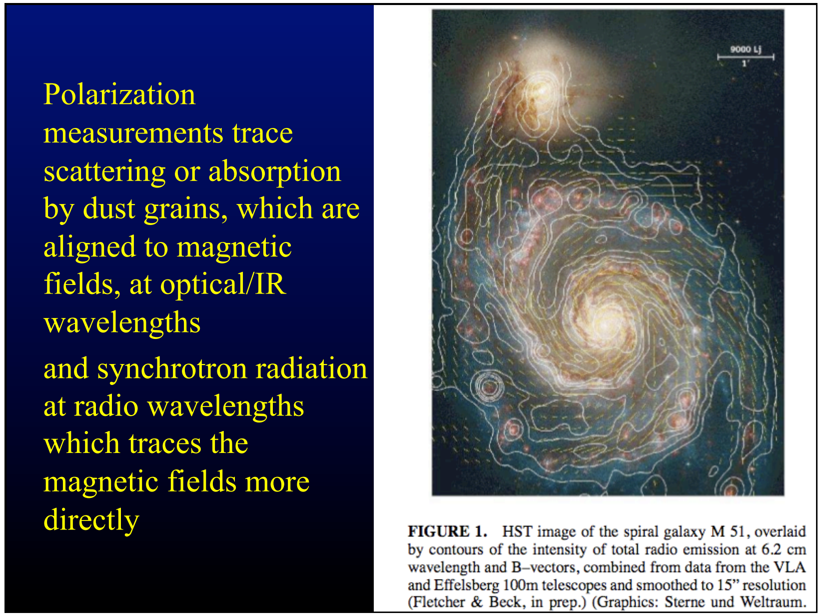
Interstellar Polarization

Measurements towards stars: traces Galactic Magnetic Field

1: Comparison of the interstellar linear polarization and extinction along the line of sight to the reddened star HD99872. The points plot the observed polarization, and an empirical fit based on the Serkowski formula with $\lambda_{max}=0.58\,\mu m$ (continuous curve) is also shown. The extinction (dotted curve) is represented by a fit to observational data. The figure is taken from Whittet (2004) who references the data sources.

Grain Alignment and Polarization:

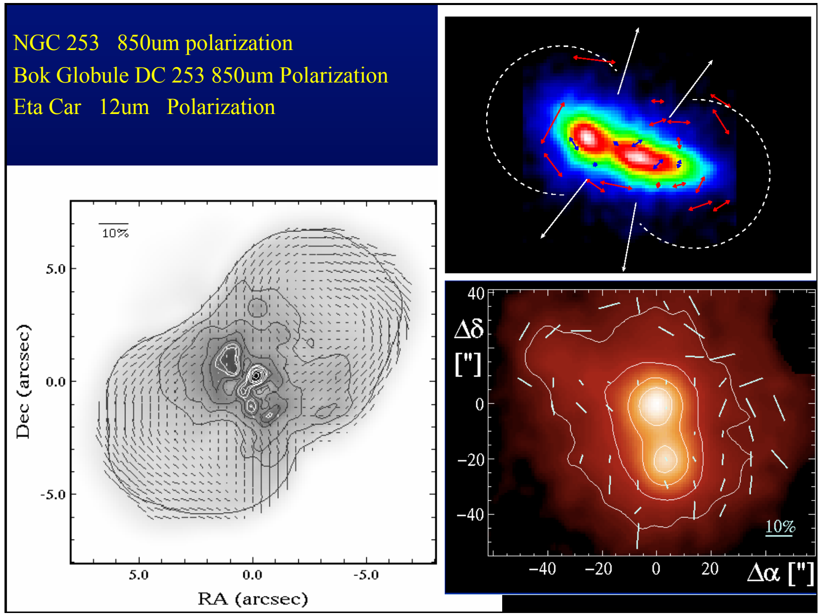
- grains generally not in equilibrium with gas T(grain) << T(gas).
- 3/2 k T(rot) ~ T(gas) --> grains spin with w~10^5 Hz.
- Dissipative torques cause the grains to spin around largest moment of Inertia.
- Barnett effect self magnetisation of spinning grain leads to precession around the B field axis
- D-G alignment J is || to B, grain long axis is _|_ to B, so absorption E-vector is || to B and emission _|_.
- Polarization depends on differing cross sections || and _|_. Grains probably not very aspherical.
- Far-IR emission only, near and mid-IR emission and absorption can be important. Need to separate components along the line of sight



Polarization measurements trace scattering or absorption by dust grains, which are aligned to magnetic fields, at optical/IR wavelengths

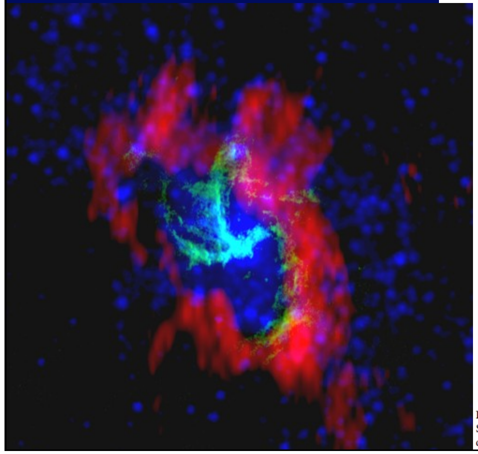
and synchrotron radiation at radio wavelengths which traces the magnetic fields more directly

FIGURE 1. HST image of the spiral galaxy M 51, overlaid by contours of the intensity of total radio emission at 6.2 cm wavelength and B–vectors, combined from data from the VLA and Effelsberg 100m telescopes and smoothed to 15" resolution (Fletcher & Beck, in prep.) (Graphics: Sterne und Weltraum.



NGC 253 850um polarization
Bok Globule DC 253 850um Polarization
Eta Car 12um Polarization

Polarization from Aligned Dust in the Galactic Centre Filaments



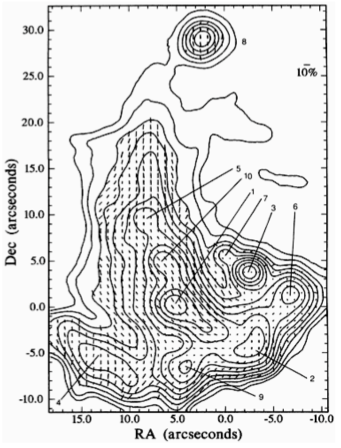
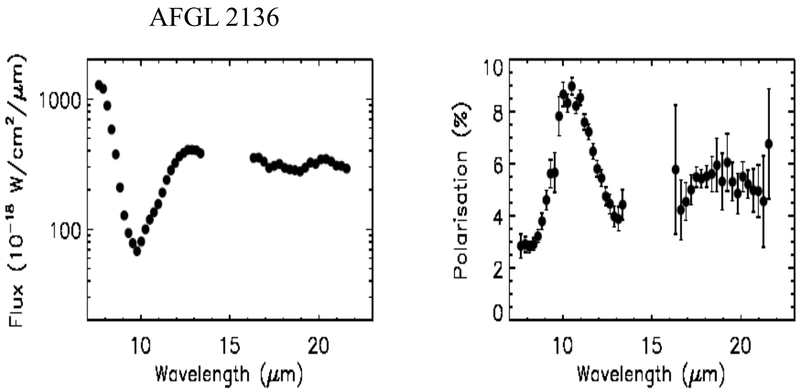
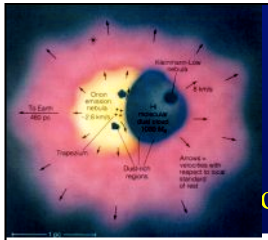


Figure 2. Surface brightness contours at 12.5 μm in the central region of SgrA overlaid with vectors orthogonal to the emissive polarization and thus denoting field directions. The contours are logarithmic with a factor $2^{1/2}$

Aligned Non-spherical Silicate Grains

Polarization peaks at 10 and 20 microns in absorption spectra

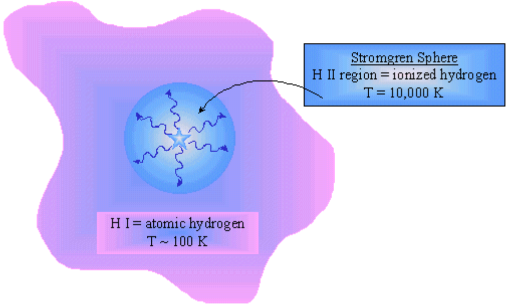




Star Forma… …on

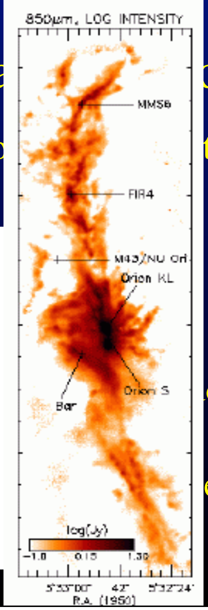
region forms, surro… …tral

omgren Sphere



Stromgren Sphere
H II region = ionized hydrogen
T = 10,000 K

H I = atomic hydrogen
T ~ 100 K



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Orion Submm Polarization

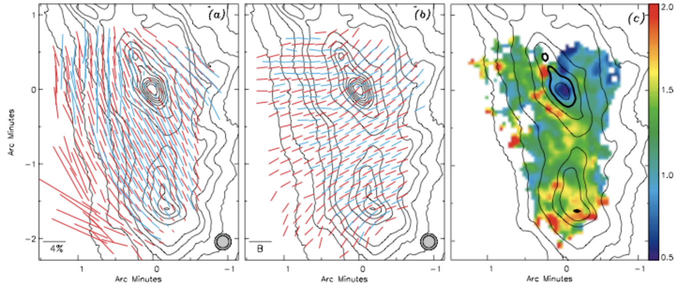
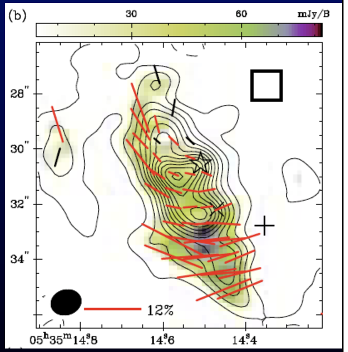


FIG. 1.—Polarimetric and photometric maps of OMC-1. Effective beam sizes (FWHM) for the photometric (9″) and polarimetric (13″) observations are shown as gray circles in (*a*) and (*b*). Coordinate offsets are measured with respect to Ori IRC 2 at $5^h35^m14.5^s$, $-5°22'31''$ (J2000.0). KL is the northernmost flux density peak coincident with the coordinate origin and KHW/Orion-south is the peak ~1.5′ to the south. Only polarization data satisfying $P > 3\sigma_p$ are included. (*a*) 350 (*red*) and 450 (*blue*) μm polarization vectors superposed on 350 μm flux density contours. Contours are drawn at 2, 4, 6, 8, 10, 20, …, and 90 percent of the peak (≈780 Jy per 9″ beam). (*b*) Inferred magnetic field vectors at 350 and 450 μm drawn with a constant length (i.e., not proportional to the polarization amplitude); contours as in (*a*). (*c*) The color scale shows the polarization ratio between the two wavelengths, $P(450)/P(350)$. Contours at 350 μm are drawn at 4, 6, 10, 20, 30, 50, and 80 percent of the peak flux density; the 50% contour is drawn thicker (see Fig. 4).

Orion BNKL Core

- Higher resolution with the SMA
- 870um (Tang et al 2010)
- Complex field geometry
- Toroidal disk wind-up, outflows?



Wavelength Dependence of Polarization

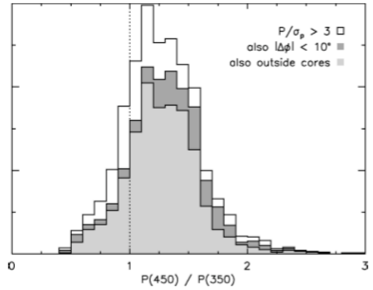


Fig. 2.—Histogram of the 450 μm/350 μm polarization ratio. All data shown here have been limited to only those points where $P \geq 3\sigma_p$ at both wavelengths. Also shown are histograms where data points satisfy the additional criteria that the position angle rotate by less than 10° between the two wavelengths ($|\Delta\phi| < 10°$) and that the points be at least 20″ away from the two submillimeter flux density peaks KL and KHW.

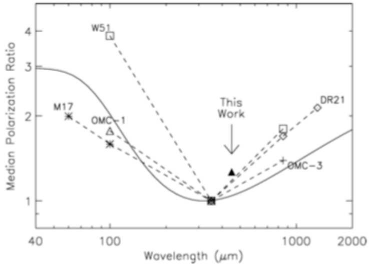
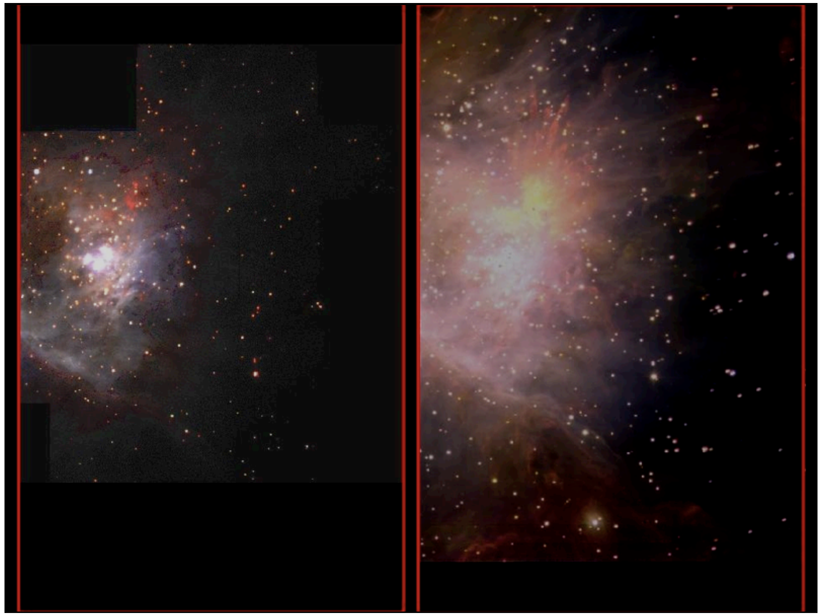


Fig. 3.—Far-infrared and submillimeter polarization spectrum, normalized at 350 μm. The 450 μm/350 μm OMC-1 comparison from this work is shown as a filled triangle. The 850 μm/350 μm comparison in W51 (*open squares*) uses data at 850 μm from Chrysostomou et al. (2002) and 350 μm data from Dotson et al. (2008). This ratio is calculated in the same manner as for all other data points, which are from Vaillancourt (2002). The solid curve is a two-component dust model (see text).

Vaillancourt et al 2008

The Orion Nebula

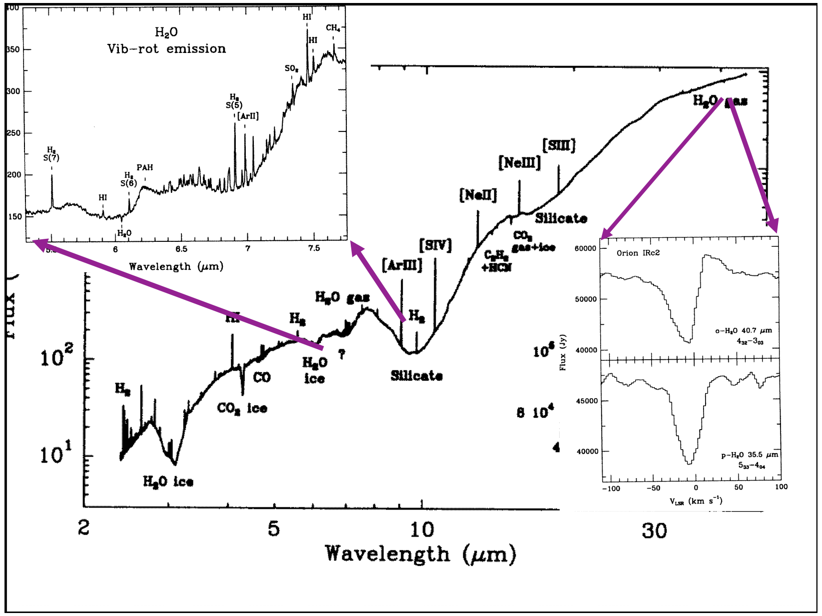
- Intensively studied, bright object
- Nearby Massive Star Formation region
- ~450 pc away 0.1 arcsec = 50pc
- Excited by Hot (50000K) Stars
- Young stars form in molecular material behind the Trapezium
- Violent outflow and shocks
- Ionization fronts at the edge of the nebula.



The Orion Nebula

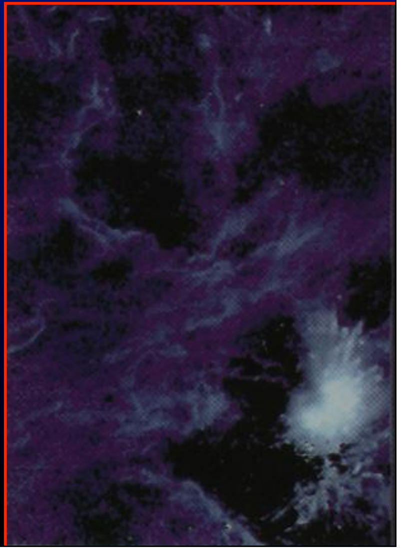
Spitzer Space Telescope • IRAC
Hubble Space Telescope • ACS • WFI

Infrared and Visible Views of Orion (Spitzer + HST)



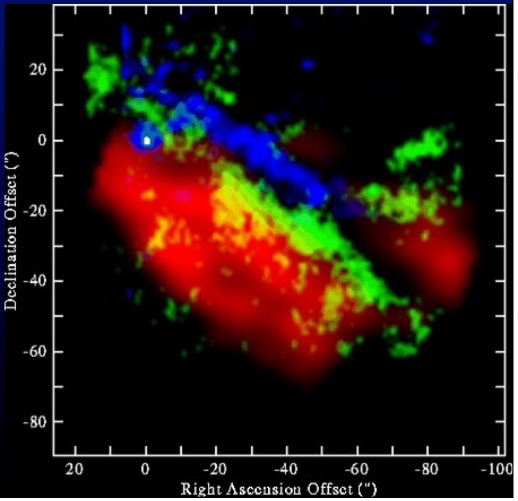
Ionization Fronts

- Orion Bar SE of Nebula
- Ionization front at edge of Stromgren Sphere
- C^+, O^+ etc
- H_2 and other molecules
- Narrow IR emission bands between 3 and 13µm
- Small C-rich grains or large molecules
- Stochastic heating



Orion Bar

- Blue 3.3um PAH
- Green H2
- Red CO



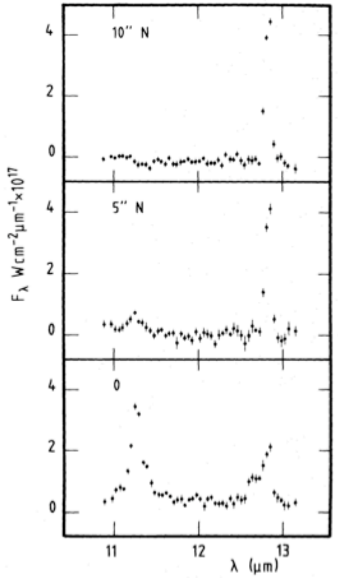
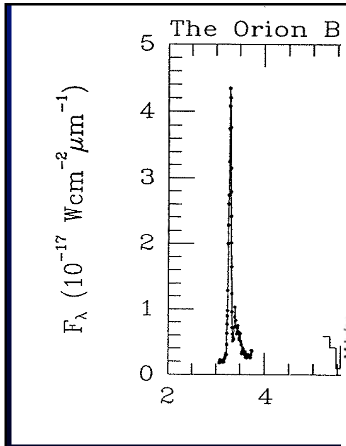
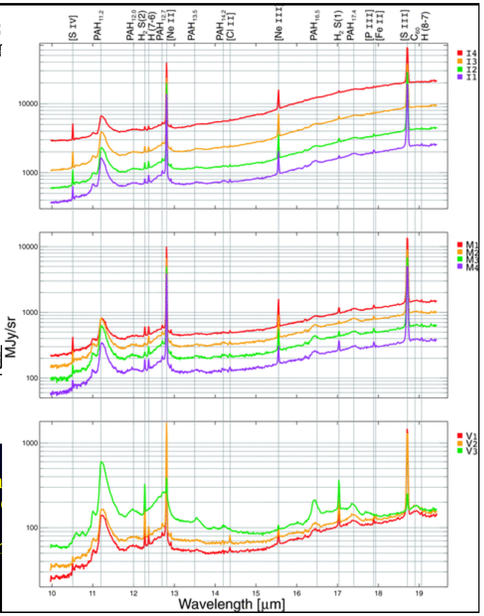
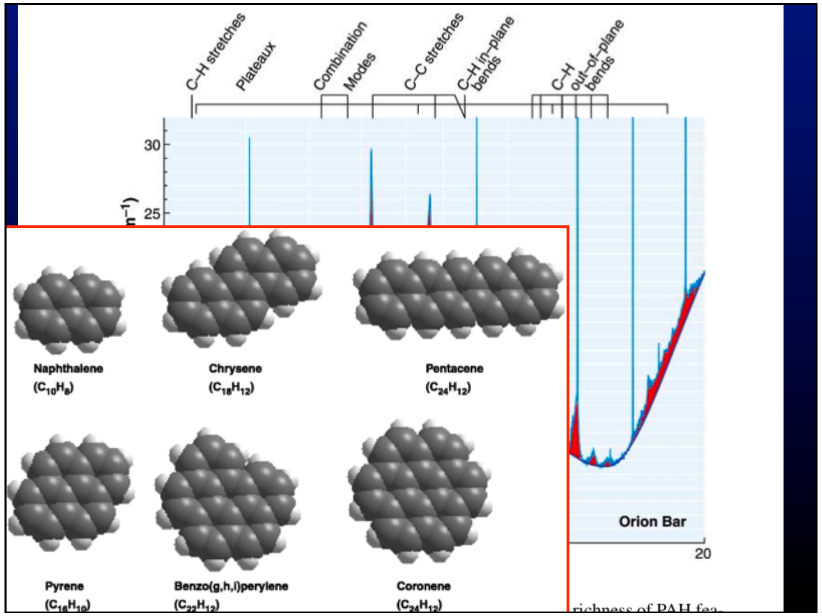


Figure 2. Spectra between 11 and 13 μm from 10 arcsec north to 20 arcsec south of position 4 in the Orion bar.





Narrow but resolved emission ban
Coincident with hydrocarbon bon
C-H Stretch, bend
Polycyclic Aromatic Hydrocarbo



richness of PAH fea-

C_{60} Buckminsterfullerene

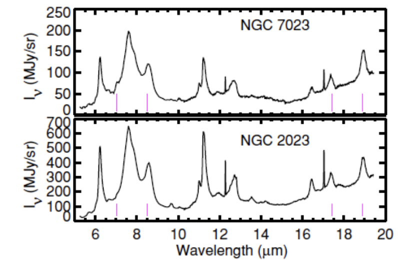
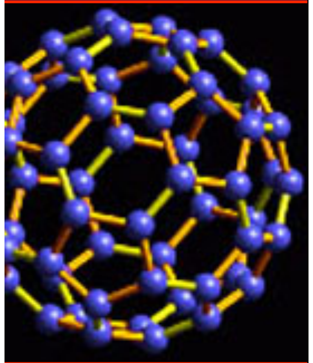
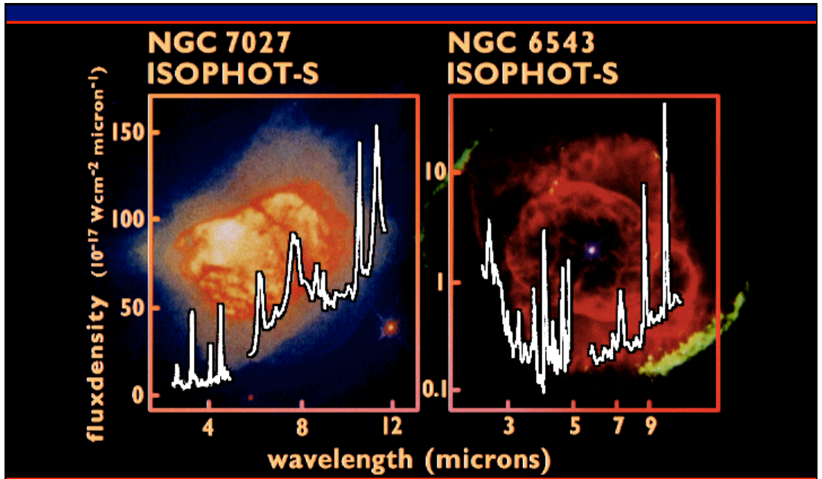


Figure 1. *Spitzer*-IRS spectra (solid curves) of NGC 7023 (25″ east, 4″ north of HD 200775; top) and NGC 2023 (29″ west, 8″ south of HD 37903; bottom), obtained with the short-wavelength low-resolution module (SL; 5.2–10.0 μm; $\lambda/\Delta\lambda$ = 60–120) and the short-wavelength high-resolution module (SH; 10.0–19.5 μm; $\lambda/\Delta\lambda = 600$). We mark C_{60} lines at 7.04, 8.5, 17.4, and 18.9 μm (vertical lines). The strong emission feature at 8.6 μm is due to PAHs. H_2 emission lines fall at 9.66, 12.3, and 17.0 μm.



Sellgren et al 2010



- Comparison with laboratory IR spectra
- But conditions very different (ionized, isolated)

Stochastic emission

Small grains have a small cross section σ_{gr} and so absorb high energy photons only occasionally from the interstellar radiation field.

They also have a small thermal capacity, so the temperature increases sharply on photon absorption

This leads to thermal spiking, rather than equilibrium thermal emission

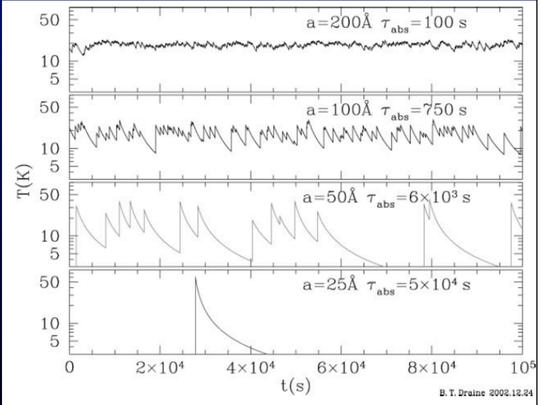


Figure 13 A day in the life of four carbonaceous grains, heated by the local interstellar radiation field. τ_{abs} is the mean time between photon absorptions (Draine & Li 2001).

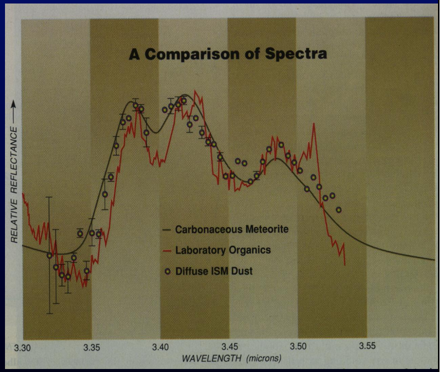
PAHs in the ISM

- Mid-Infrared PAH bands trace the interface regions between nebulae and the ISM
- Reveal a new region of excited molecules and low-ionization gas
- New insights into chemistry and grain heating
- Pose new questions about molecule formation
- Join the long-standing Diffuse Interstellar Band

The Triffid Nebula: ESO and Spitzer

Interstellar and Solar System Dust

- Meteorite Laboratory analysis
- Isotopic Ratios
- Carbonaceous Chondrites
- Spectral Analysis
- Organic materials - hydrocarbons



Enrichment of the ISM

- injected from stars:

Type	Total Number	Amount (M_O /yr)
Mira	9000000	2
OH/IR	60000	2
Carbon	40000	0.6
Supernovae	1/50yr	0.2
M Supergiants	5000	0.2
OB Stars	50000	0.1
WR Stars	3000	0.05
PN	4000	0.2
Novae	50/yr	0.0001

Galactic Recycling

- Stellar outflows ~ 5 M_O /yr
- But similar amount used up in star formation
- But leads to steady enrichment of heavy elements, nucleosynthesis products
- Different dust products from different types of star
- Dust destruction by supernova shocks