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

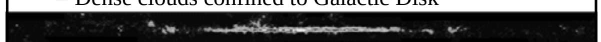
Why study the ISM?

- 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
- Dark Matter?

The Interstellar Medium in our Galaxy

- From the Solar System to the edges of the Galaxy

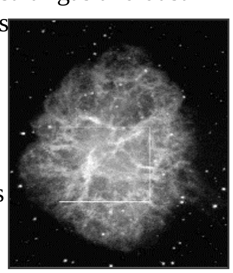
  - Dense clouds confined to Galactic Disk



  - Galactic Halo
  - Galactic Fountains
  - Abundance gradients
  - Spiral Structure

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

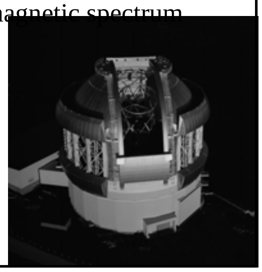


Phases of the ISM

- 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



Assume cosmic elemental abundance values for the interstellar material

Measure elements in the gas phase and infer missing material condensed into dust grains

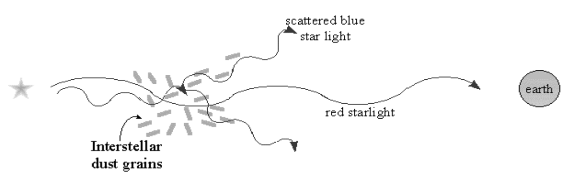
Interstellar atoms and molecules absorb light emitted by stars, absorption lines

Reflection nebulae

Emission nebulae excited by hot stars

Probing the ISM : Interstellar Reddening

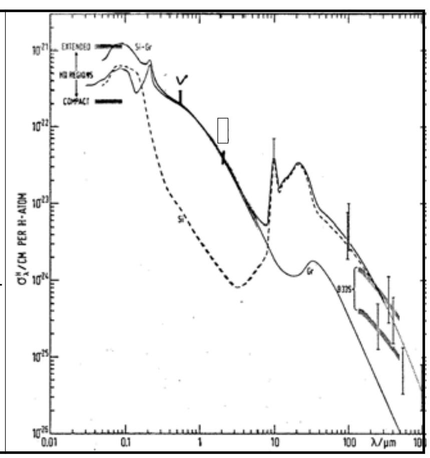
- Distant stars appear redder than nearby examples
- Attributed to scattering by small particles <λ - cosmic dust
- scattering efficiency falls with increasing wavelength and becomes unimportant in the infrared where absorption dominates
- Extinction = scattering + absorption Structure in the extinction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



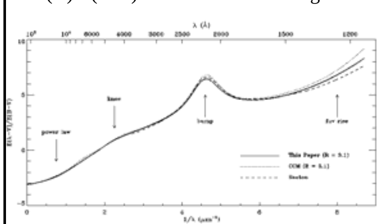
Interstellar Extinction Curve

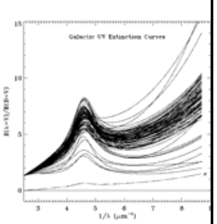
- Generally not possible to look at one object to cover the whole spectrum - need to patch together observations from UV to IR
- Different lines of sight reveal differences in detail Changing dust grain sizes and/or mixture of species, but overall shape is maintained
- Dust grains absorb starlight, heat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

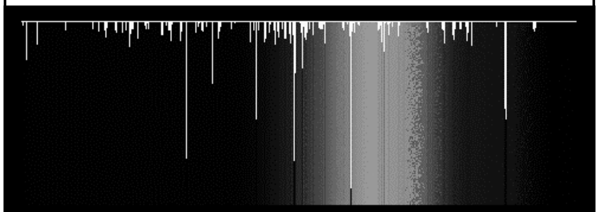


- Often given as E(B-V) or A(V)
- Standard curves, but beware of special regions (e.g. Orion)
- Often classed by R = E(B-V)/A(v) [~ 3.1] = ratio of selective to total extinction
- Smaller variations in the IR, but not well characterized $A(\lambda) \sim \lambda^{-1.8}$
- Substantial variations in the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





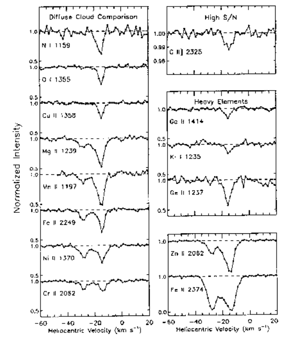
Diffuse Interstellar Bands



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

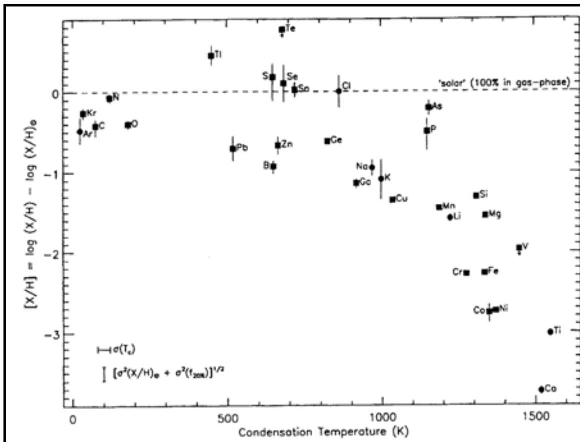
Probing the ISM
The diffuse ISM at short wavelengths

- 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 ~ 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 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 + Infrared Space Observatory

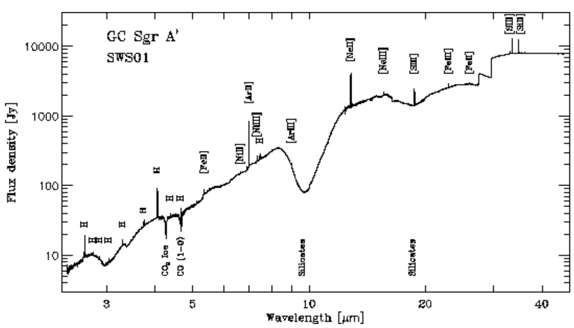
The path to the Galactic Centre

- ~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



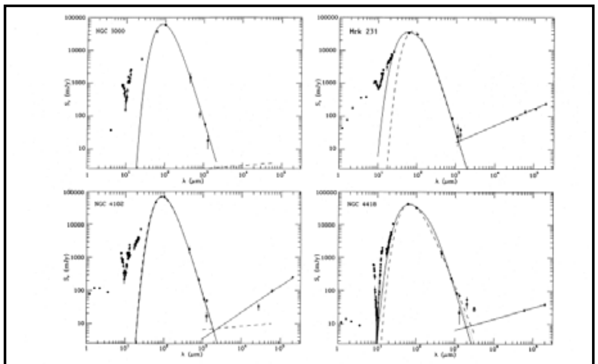


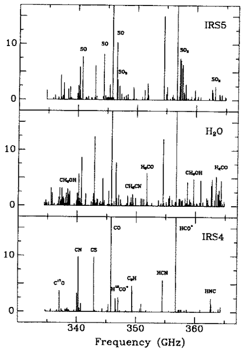
Figure 1. Infrared-to-radio emission from the target galaxies. The near- and mid-infrared photometry and spectroscopy are from Roche et al. (1991), except for the near-infrared photometry of Mrk 231 which is taken from Rieke (1976) and the 4.1-µm datum for NGC 6000 which is the continuum level reported 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.

Dust in Galaxies

- 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 $\lambda < 60$µm
  - could be significant dust mass hidden in cold component
  - may need to correct for synchrotron or free-free emission

Probing the ISM : Molecular Cloud Gas

- Cold, dense clouds of molecular gas.
- Gravitationally bound massive clouds
- Temperatures ~10-30 K, mostly molecular gas with some molecules frozen on to dust grains e.g. water, methanol etc.
- Best probed at microwave frequencies
- Most abundant molecules H_2 and CO, but H_2 has no dipole moment, so does not radiate effectively



Simple Hydrides, Oxides, Sulfides, Halogens and related molecules

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

Nitriles and Acetylene derivatives

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

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

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

Cyclic Molecules

C_3H_2	SiC_2	c-C_3H	CH_2OCH_2

Molecular Ions

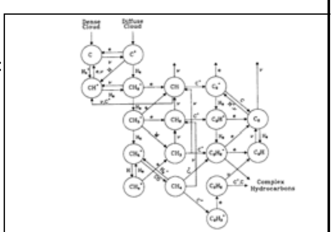
CH^+ (VIS)	HCO^+	$HCNH^+$	H_3O^+	HN_2^+
HCS^+	$HOCO^+$	HC_3NH^+	HOC^+	H_3^+ (IR)
CO^+	H_2COH^+	SO^+		

Radicals

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

Probing the ISM : Molecular Cloud Dust

- Cold Dust emits at far-infrared wavelengths
- T~ 30K => Peak emission >100 microns
- Large columns of cold dust scatter and absorb at shorter wavelengths.
- Absorption bands give dust columns and identity of dust species, and reveal icy mantles condensed on grain cores
- Complex reaction sequences : astrochemistry



Initial steps in the gas-phase carbon chemistry in diffuse and dark clouds.

Grain Alignment:

grains generally not in equilibrium with gas T(grain) << T(gas).

3/2 k T(rot) ~ T(gas) --> grains spin with ω~105 Hz.

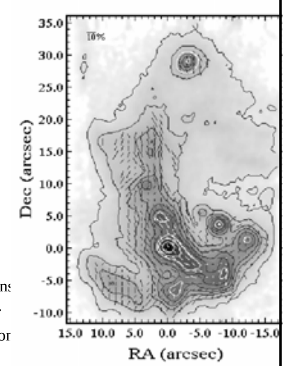
Dissipative torques cause the grains to spin around largest moment of Inertia.

Barnett effect self magnetisation of soinning grain leads to precession around the B field axis

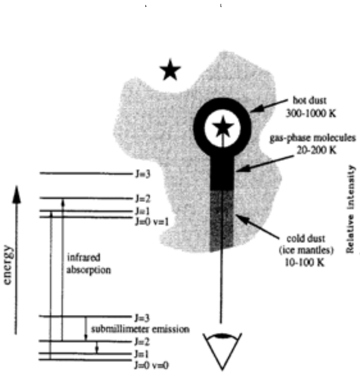
D-G alignment J is || to B, grain long axis is _|_ to B, so absorption E-vector is || to B and emission _|_.

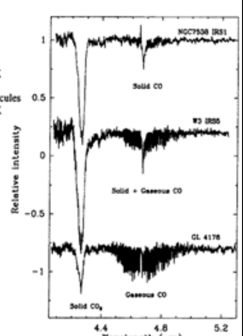
Polarization depends on differing cross sections || and _|_. Grains probably not very aspherical.

Far-IR emission only, near and mid-IR emission and absorption can be important. Need to separate components along the line of sight



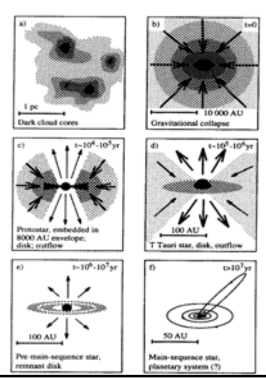
Dense Cloud
Diffuse Cloud

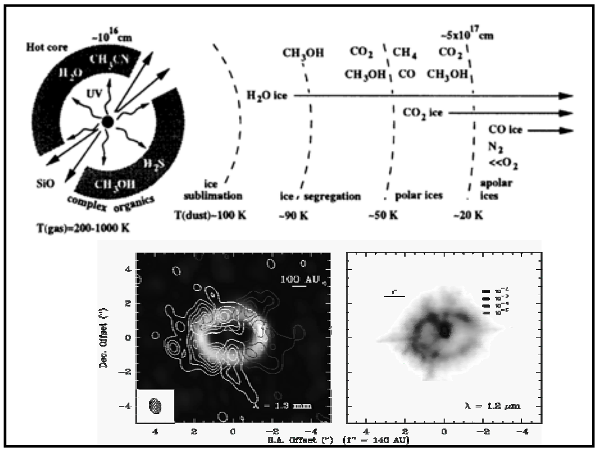




Molecular Clouds and Star Formation

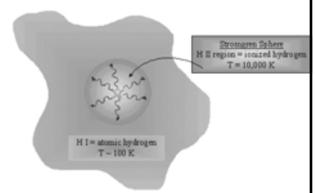
- Stars forming in Molecular Clouds heat up the gas and dust and drive chemical reactions
- Initial infall under gravity is reversed as the nascent star heats up. Icy mantles evaporate and dust grains are annealed
- Outflow from the young star drives shocks through the cloud
- Shocks heat grains and may destroy them, breaking them into molecules.

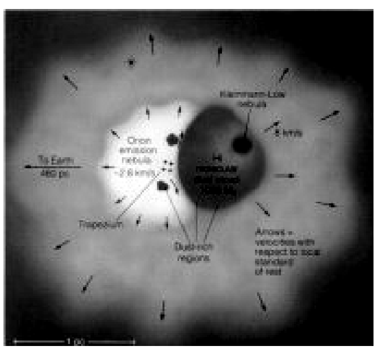


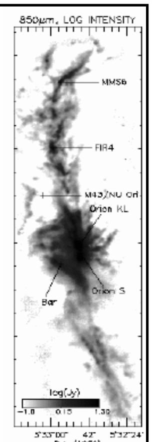


Star Formation Region

- Ionized (HII) region forms, surrounded by neutral material. Stromgren Sphere
- Dust is driven from central region
- Non-ionizing radiation (λ> 100 nm) creates a photodissociation zone around the HII region
- Radiation which cannot ionize Hydrogen, but does ionize C,N,O and some molecules
- Molecular Hydrogen emission and more complex organic materials

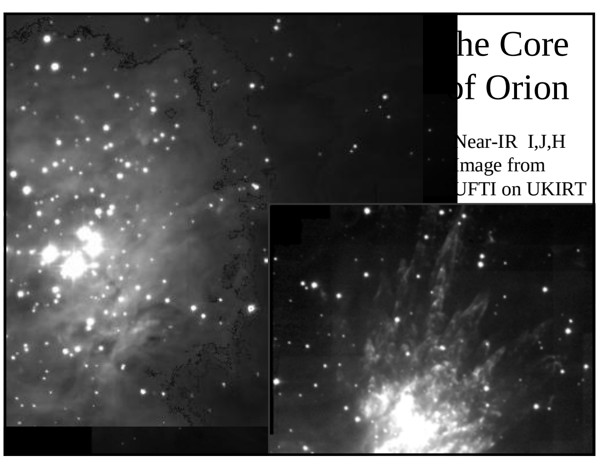






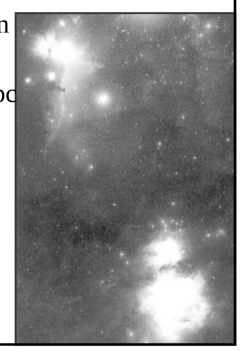
The Orion Nebula

- 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.



he Core of Orion

Near-IR I,J,H image from UFTI on UKIRT

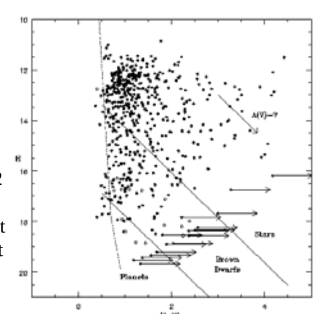


Orion Results

Hot young stars dominate ionization and proplyd silhouettes

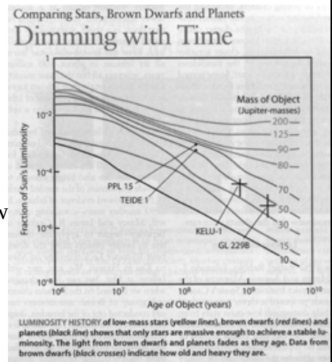
From extinction-corrected fluxes, infer temperature and luminosity of sources

Adopted ages between 0.5 and 2 m.year give 1/3 of point sources below the stellar limit, and about 3% below the brown dwarf limit - lowest mass object is ~8 Jupiter masses

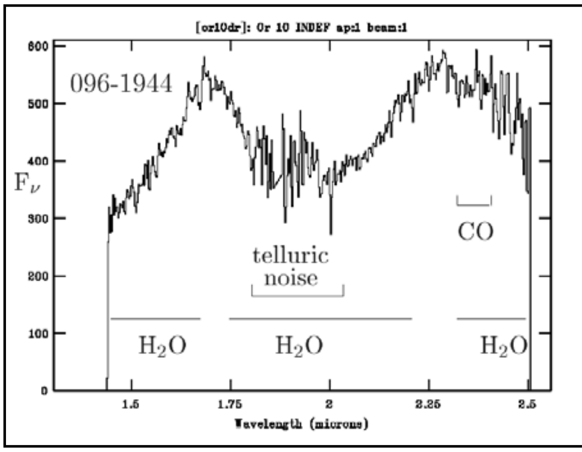


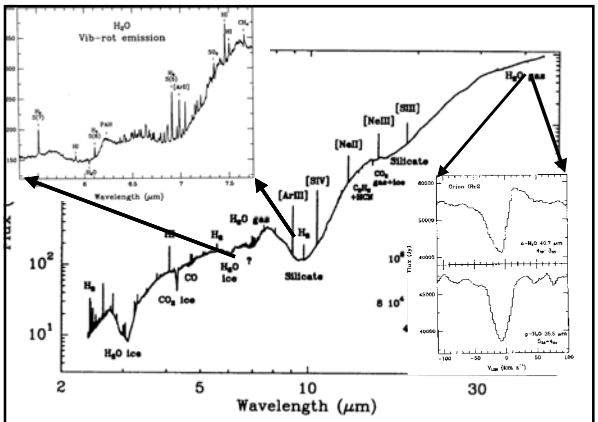
Orion Results

- Models of young, low mass objects are under development and may improve identification of planetary mass objects
- Follow-up spectroscopy of 20 objects confirms low mass with deep water bands and different band profiles to field brown dwarves



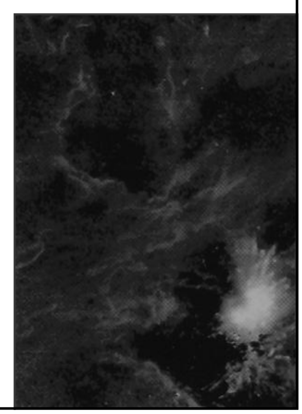
LUMINOSITY HISTORY of low-mass stars (yellow lines), brown dwarfs (red lines) and planets (black line) shows that only stars are massive enough to achieve a stable luminosity. The light from brown dwarfs and planets fades as they age. Data from brown dwarfs (black crosses) indicate how old and heavy they are.

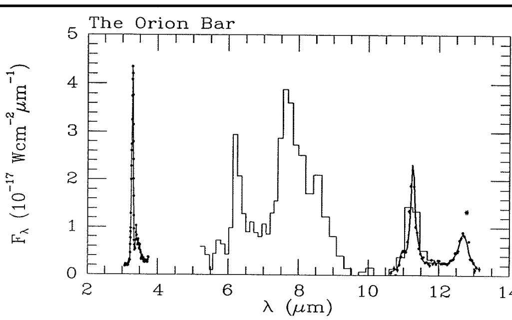




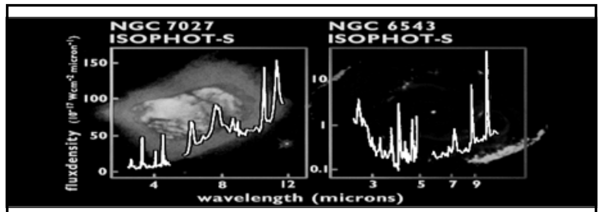
Ionization Fronts

- 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



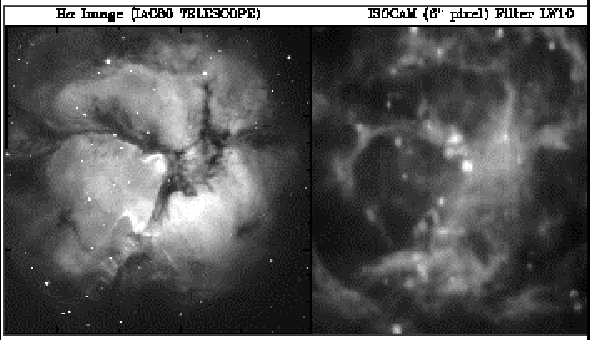


Narrow but resolved emission bands
Coincident with hydrocarbon bond transitions
C-H Stretch, bend
Polycyclic Aromatic Hydrocarbons



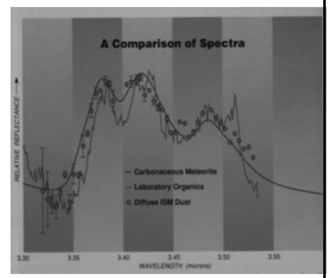
- Precise identity uncertain, but PAH
- Prominent at the edge of Ionized Regions
- Destroyed by high energy photon
- Excited by UV/Visible photons
- Most prominent in carbon-rich nebulae
- Bending and stretching vibrations of hydrocarbon bonds
- Comparison with laboratory IR spectra
- But conditions very different (ionized, isolated)

PAHs in the ISM



Interstellar and Solar System Dust

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



Enrichment of the ISM

- injected from stars:

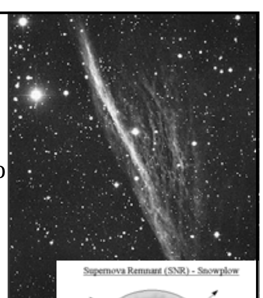
Type	Total Number	Amount (M_O /yr)
Mira	9000000	2
OH/IR	60000	2
Carbon	40000	0.6
Supernovae	1/50yr	0.2
M Supergiants	5000	0.2
OB Stars	50000	0.1
WR Stars	3000	0.05
PN	4000	0.2
Novae	50/yr	0.0001

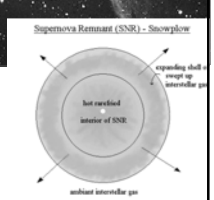
Galactic Recycling

- 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

The Violent ISM

- Supernovae - violent explosions
- Ejecta expand at speeds up to 20,000 km/s
- Contain substantial amounts of Fe, Ni
- Sweep up interstellar material
- Collide with ISM clouds
- Violent shocks destroy molecules and dust



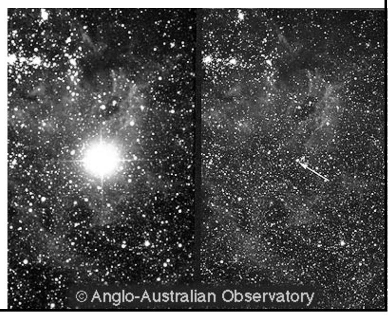


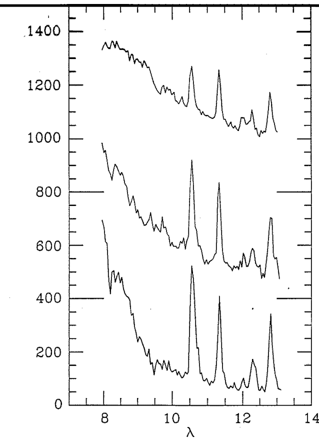
The Violent ISM

- Supernovae explosions inject 10^{44} J and > 10 $M_{\odot}$ of enriched material into the ISM (+ neutrinos)
- Ejecta expand at speeds up to 20,000 km/s
- Onion skin structure with different abundances in different layers
- Contain substantial amounts of Fe, Ni - molecule and dust condensation as the ejecta expand and cool
- Powered by radioactive decay of Ni, Co, Ti etc
- Sweep up interstellar material
- Collide with ISM clouds
- Violent shocks destroy molecules and dust

Supernova 1987A

- Exploded in the Large Magellanic Cloud in February 1987





SN1987A with the Hubble Space Telescope