Evolution from AGB to Planetary Nebulae

Sun Kwok

The most interesting period in stellar evolution

- Nowhere else in the life of a star that so much happen over so little time
- AGB: 10^5 years of intense mass loss
- PPN: a factor of 10 change in stellar temperature in a few thousand years
- PN: 10^4 years

The richest laboratory

- Nucleosynthesis
- Creation of molecules and grains
- Stellar winds: fast and slow, isotropic and collimated
- Radiation: from radio to x-ray
- Interaction: matter with matter (dynamics), radiation with matter (photoionization, photodissociation)

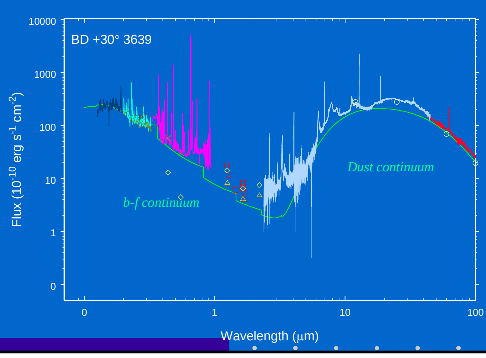
End of AGB

- Depletion of H envelope by mass loss
- Increasing T_e as the result of decreasing M_{en}
- Enhanced equatorial mass loss leading to creation of torus?
- Initiation of new fast, collimated (?) wind

Beginning of PN

- Photoionization: recombination lines of H and He, collisionally excited lines of metals, b-f and f-f continuum
- Photodissociation: PDR
- Gas-phase and grain chemistry

Remnant AGB dust envelope in PN



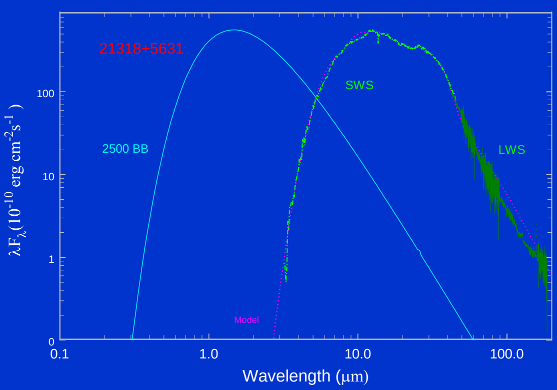
Observational techniques

- Optical: narrow band imaging, integral field spectroscopy
- Infrared imaging: where is the dust?
- Infrared spectroscopy: what kinds of dust?
- mm/submm imaging and spectroscopy: what kinds of molecules and where are they?

Materials inherited from AGB

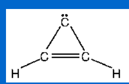
- Molecular and dust envelope: up to several solar masses
- From mm/submm molecular imaging, the AGB CSE is largely spherically symmetric
- Density and temperature structures can be determined from molecular and IR observations

Chemistry and morphology



Gas phase molecules in the stellar wind

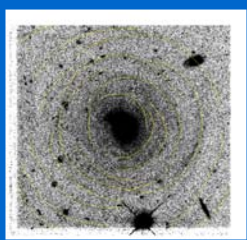
- Rotational transitions of over 60 molecules have been detected in the circumstellar envelopes of AGB stars
- Inorganics: CO, SiO, SiS, NH_3, $AlCl$, ..
- Organics: C_2H_2, CH_4, H_2CO, CH_3CN, ..
- Radicals: CN, C_2H, C_3, HCO^+
- Rings (C_3H_2), chains (HC_9N)



Dust formation in the stellar wind

- Amorphous silicates and silicon carbide
- Refractory oxides: corundum (α-Al_2O_3): 12.7 μm, spinel (e.g. $MgAl_2O_4$): 12.95 μm, rutile (TiO_2): 13.4 μm, periclase (MgO), glass (amorphous SiO_2): 12.3 μm

Morphology from scattered light



9 non-concentric arc segments

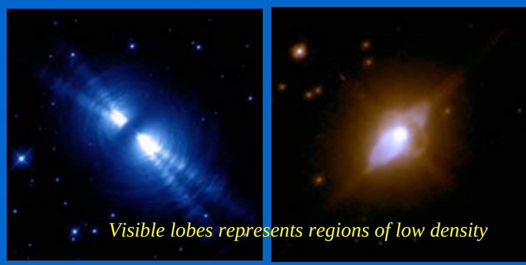
Spherical envelope but bipolar core

Post AGB

- First interaction between fast and slow winds
- Craving of cavity in AGB circumstellar envelope

Reflection nebulosity

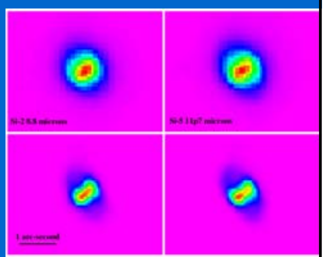
Collimated outflow



Searchlight beams: wall of cavity

Equatorial disk

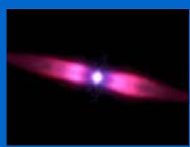
Where is the dust?

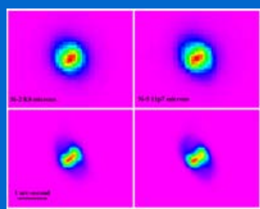


TReCX in South and Michelle in North

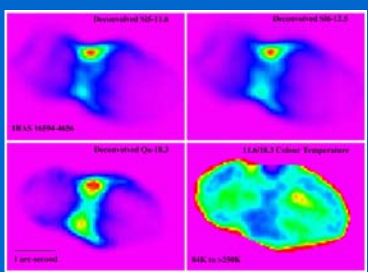
Mid-IR imaging at Gemini

TReCX in South and Michelle in North

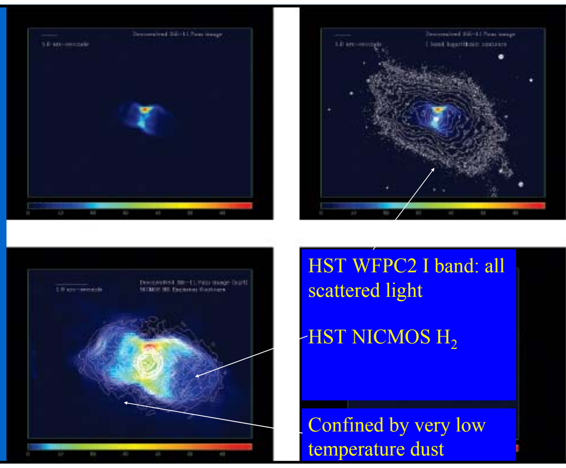




Dust in the torus and in the lobes

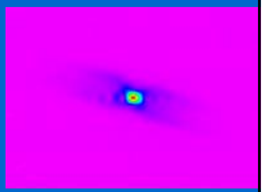


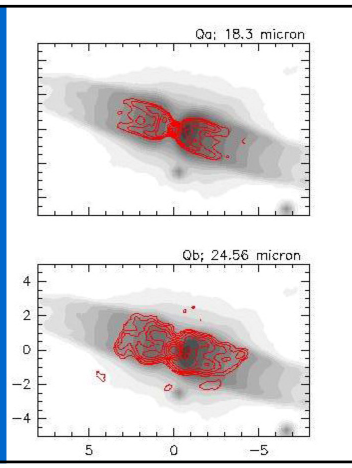
Volk et al. 2005



At 20 µm we are still seeing warm dust

Hen 3-401





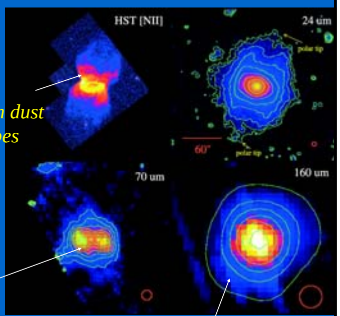
Gemini T-ReCS

The torus is cold

Where is the cold dust?

Multiband imaging photometer for Spitzer

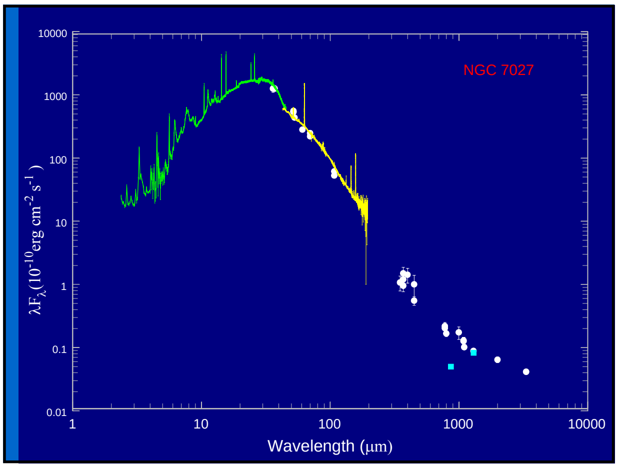
Warm dust in lobes



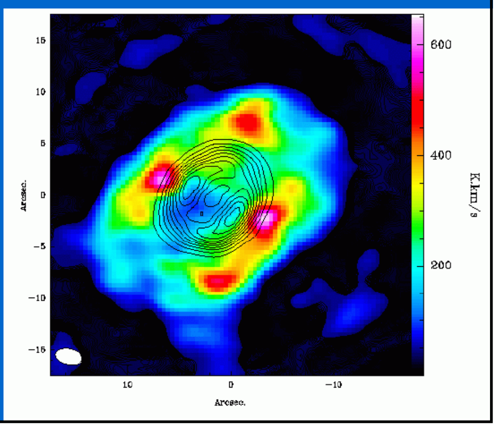
torus

Su et al. 2004

AGB remnant



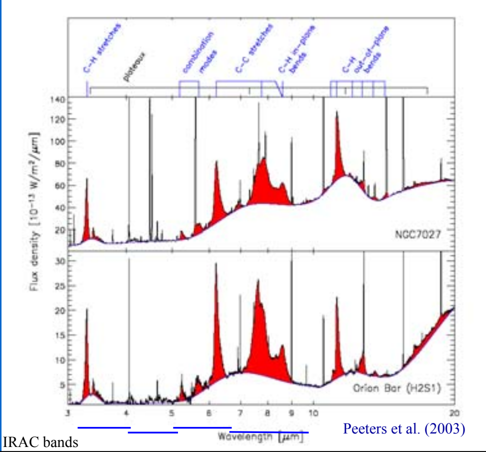
Where are the molecules?



CO outside of the ionized shell

Warm dust as tracers of PN

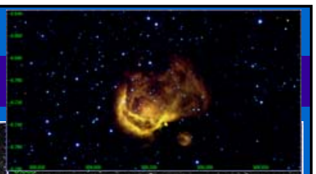
- Galactic Legacy Infrared Mid-Plane Survey Extraordinaire
- 220 sq. deg.: ℓ=-65º→-10º, +10º→+65º; b=-1º→+1º
- 3.6, 4.5, 5.8, 8.0 µm, 2″ resolution
- 400 hours (2004 March 9-Nov 1)
- 10^7-10^8 sources

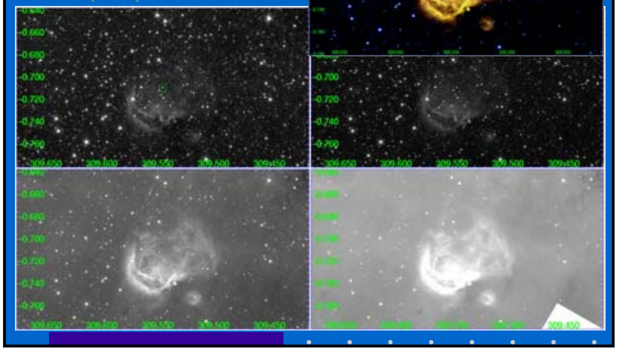


IRAC bands

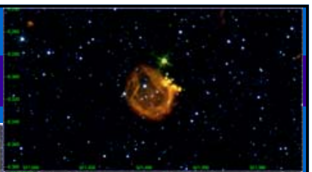
Peeters et al. (2003)

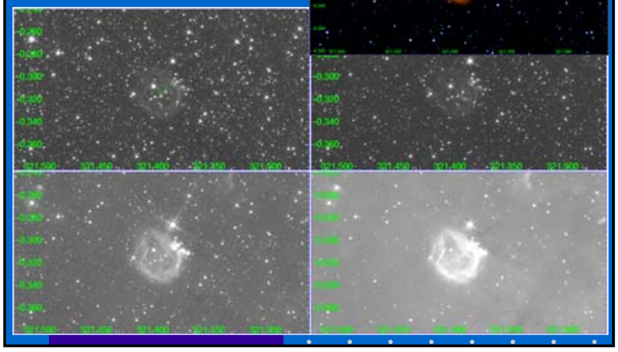
309.5-00.7 (in new PN catalogue):
RA (2000): 13h49m52.1s ,
Dec(2000): -62°49’41”

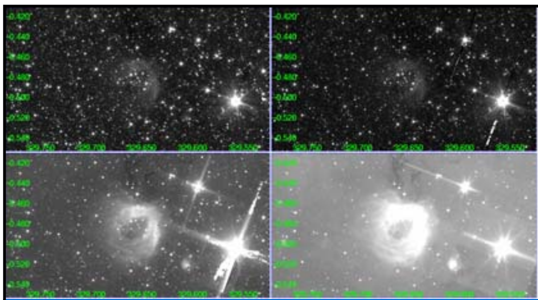




321.3-00.3 (in new PN catalogue):
RA(2000):15h17m30.0s
Dec(2000): -57°50’59”



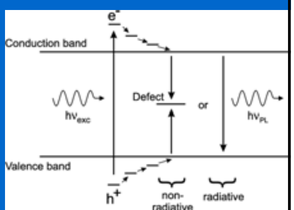




329.6-00.4

Extended Red Emission

- Broad (Δλ~80 nm) emission band peaking between 650 and 800 nm.
- Photoluminescence powered by far UV photons

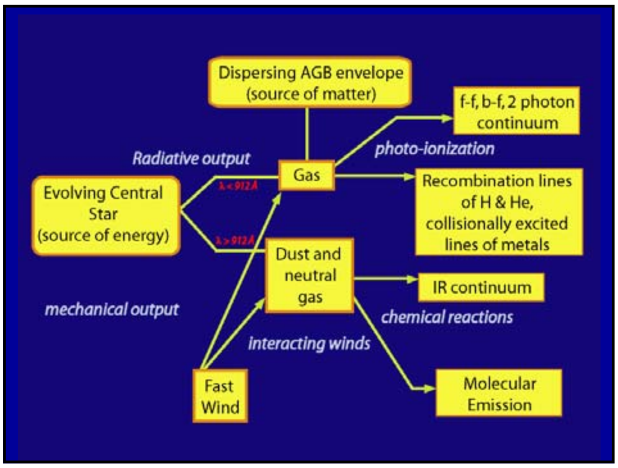


HST ACS

Evaporating planetisimals?

Morphology

- Successes: explanation of the multishell structure (shells, crowns and haloes) through the 1-D ISW model
- Challenges: FLIERS, 2-D rings, arcs, point-symmetric structures, multipolar nebulae

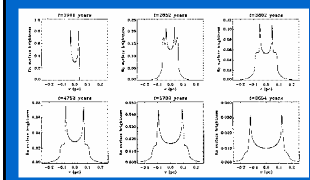


Shells, Rims, Crowns, and Haloes

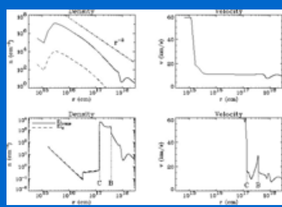
NGC 5979
NGC 6578
NGC 2022
NGC 6629
NGC 5882

Crowns, haloes, and multiple shells

Can only be understood with a consistent treatment of dynamics and stellar evolution



Mellema (1994)

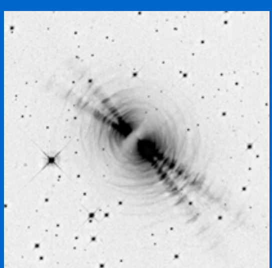


Steffen et al. (1998), Corradi et al. (2000)

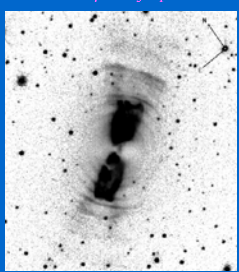
Recombination haloes? (Tylenda)
Kinematic age not reliable (Schönberner)

Circumstellar Arcs

Perfectly circular and uniformly spaced arcs

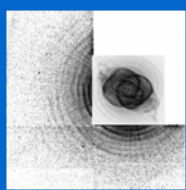


AFGL 2688: >24 arcs

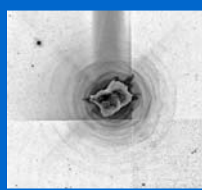


IRAS 17150-3224: >8 arcs

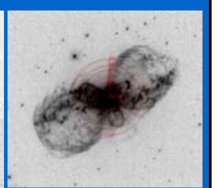
Arcs in PN



NGC 6543: >11 arcs



NGC 7027: >7 arcs



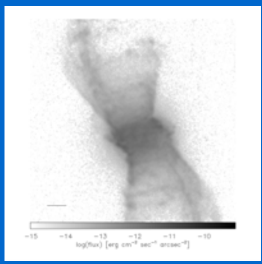
Hb 5: >6 arcs

Kwok et al. (2001)

Arcs persist through the PN phase undisturbed by fast outflow

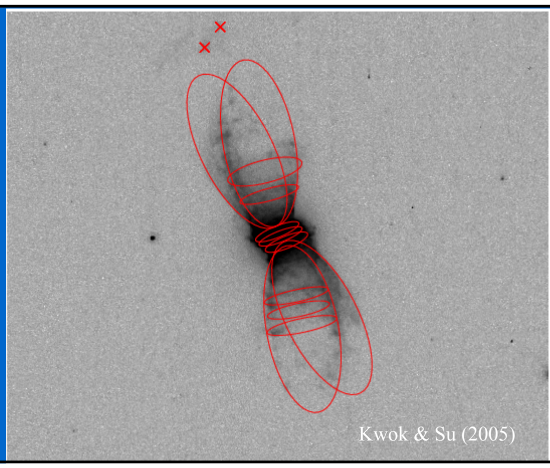
2-D rings

- Several rings can be seen in the torus and the lobes
- Plane of the rings perpendicular to bipolar axis
- Similar to rings seen in SN 1987A



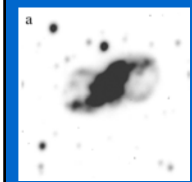
NGC 6881

Kwok & Su (2005)

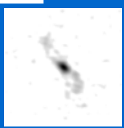


Kwok & Su (2005)

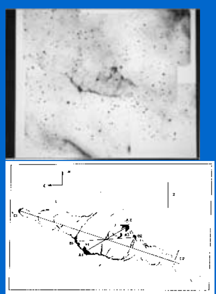
Point-Symmetric Structures



Hb5 (López et al. 1993)

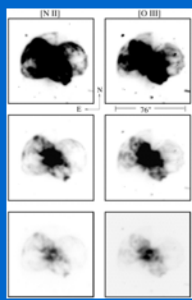


K3-35 (Aaquist & Kwok 1989)



KjPn8 (López et al. 1995)

Two pairs of lobes

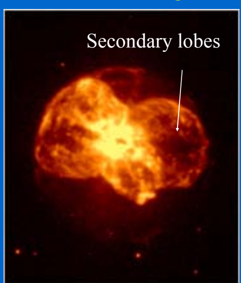


NGC 2440 (Lopez et al. 1998)

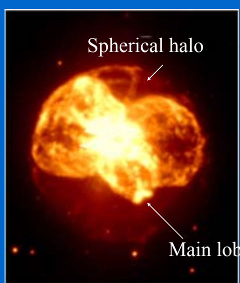
Outflow direction changing with time?

Multiple Lobes in NGC 2440

NII images taken at CFHT, Dec 16, 2002

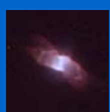


30 sec, unprocessed

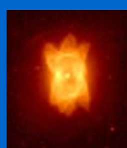


1200 sec, unprocessed

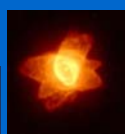
Multi-polar Nebulae



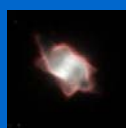
He2-447



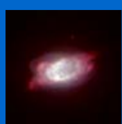
M1-37



He2-47



He2-299



IC 5117

NGC 6881

Collimation Mechanisms

- Fast wind not isotropic: mass loss rate and velocity functions of time and direction
- Rotating stars with magnetic fields (Chevalier & Luo 1994, Garcia-Segura)
- Binaries (Soker, Livio)
- BRETs: precession of wide binaries (Garcia-Segura 1997), warped accretion disks (Livio & Pringle 1996)

Theoretical techniques

- Radiation transfer: coupling between the ionized gas, molecular, and dust components
- Chemical networks
- Dynamics: 2-D coupled with stellar evolution and photoionization
- scattering

Questions

- Mechanisms responsible for changing chemistry and morphology: when and how
- Disk collimated outflow: binaries? Magnetic field?
- Multipolar structures: precession? Rotation?
- Dynamical processes that lead to arcs and rings

Questions on the distribution of neutral matter

- Far IR and submm imaging is still needed to determine the dust distribution
- Where do the UIR and ERE originate?
- What is the carrier of ERE, 21 and 30 μm features?
- What is the origin of the globules?