Life after stellar death: Planetary Nebulae and Supernova Remnants

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Overview

A. Late stages of Stellar evolution

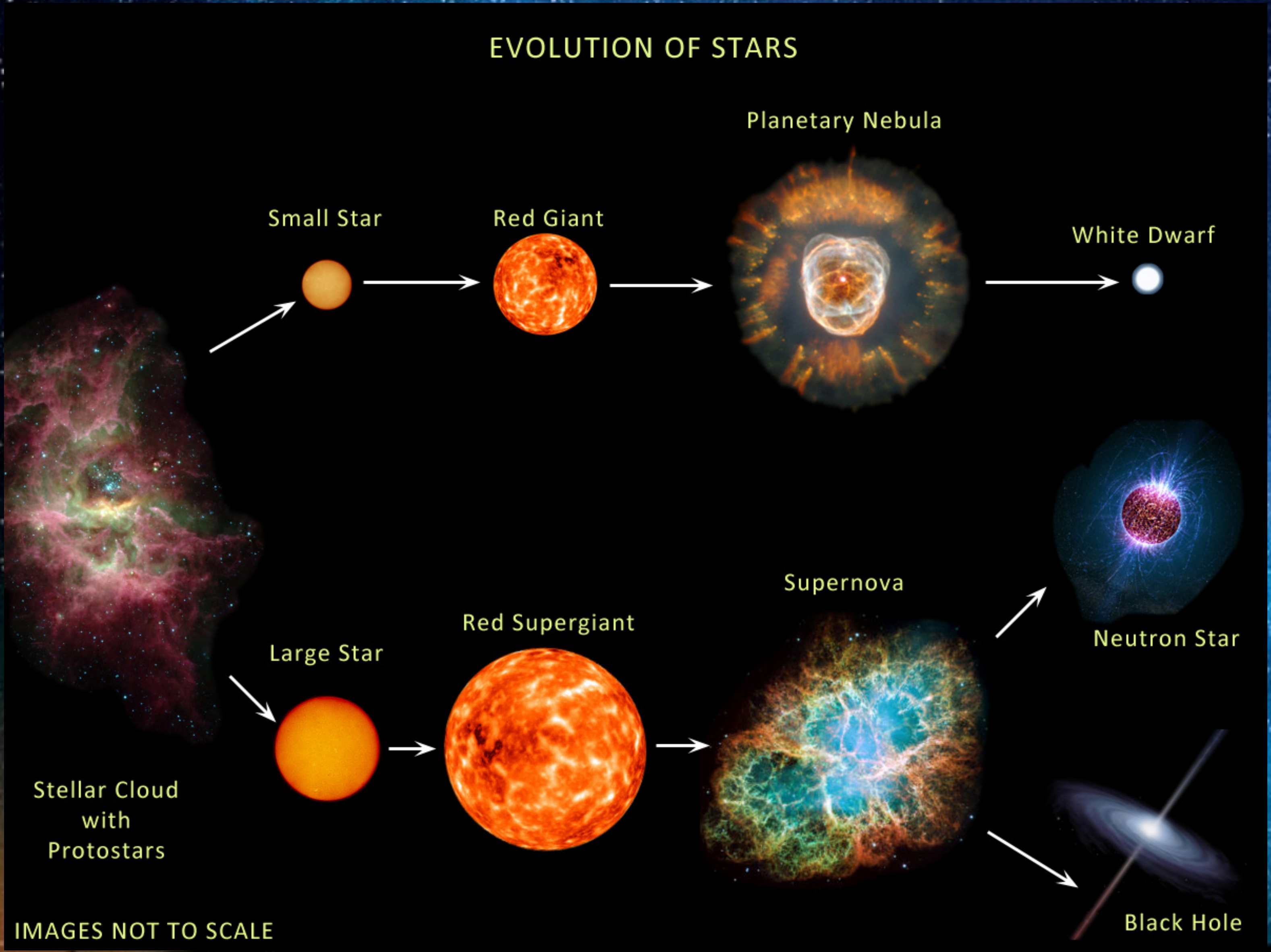
B. Planetary Nebulae

C. Supernova Remnants

D. Latest Results on PNe (KjPn 8, Helix)

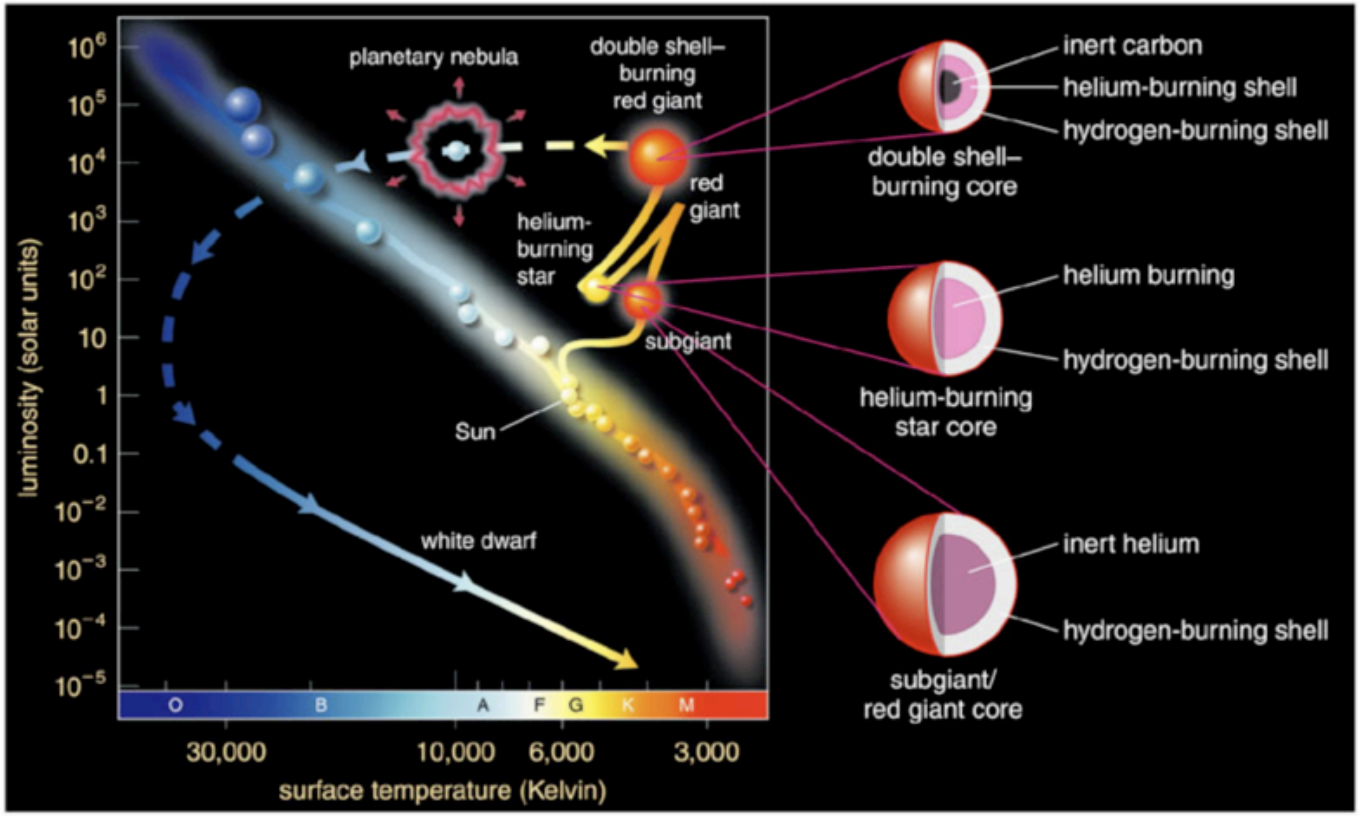
E. Latest Results on SNRs (VRO)

Late stages of stellar evolution



Planetary Nebulae

Planetary nebula is made up from the gaseous material which was ejected from the outer layers of the star in the final stage of its evolution (AGB phase).



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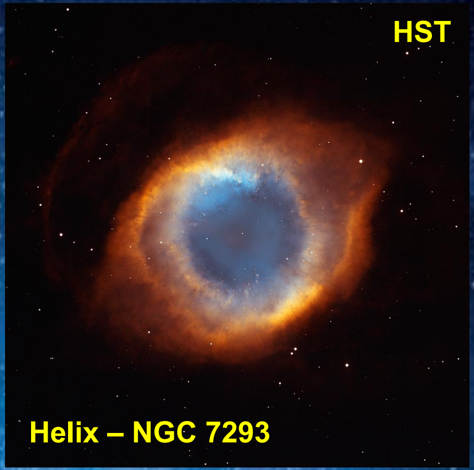
Planetary Nebulae

Central star

- Effective Temperature 40000-100000K
- Luminosity~$5*10^3 L_{sun}$
- Radius ~$0.005R_{sun}$,~$1.5R_{sun}$
- Mass Loss Rate ~10^{-10},10^{-7} M_{sun}/yr
- Mass ~$0.6M_{sun}$
- The type of central star (O or B)



Nebula

- Angular diameter 20´´- 40´´,upper limit ~20´
- Ne=10^3-10^4 e^-/cm^3 (<10^3 older, >10^4 younger)
- Te=8,000-20,000K
- Expansion velocity ~25km/s

Spectrum of PNe

Emission lines in optical wavelength

- Recombination lines (Hα, Hβ, etc)
- Forbidden emission lines ([O II] 3727A, [O III] 4959A, [O III] 5007A, [N II] 6548A, [N II] 6584A, [S II] 6717A, [S II] 6731A)

Continuum radiation

- Free-bound emission (strong at optical wavelength)
- Bremsstrahlung (strong at radio)
- Dust continuum emission

Planetary Nebulae

Why are PNe important?

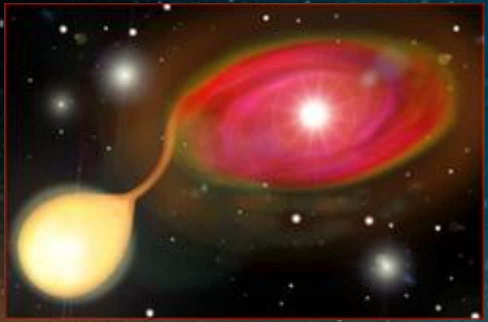
- They are useful tools of stellar evolution (stellar models)
- They play an important role in the chemical enrichment of the interstellar medium (distribution of abundances in our Galaxy)
- Their interaction with the interstellar dust (in the infrared, which show us how dust grains radiate), provide information of star-forming regions hence improve the physics of dust grains (grain models)

Supernova Remnants

A Supernova Remnant (SNR) is the expanding blast wave plowing through the ISM, resulting from the explosion of a star in a supernova.

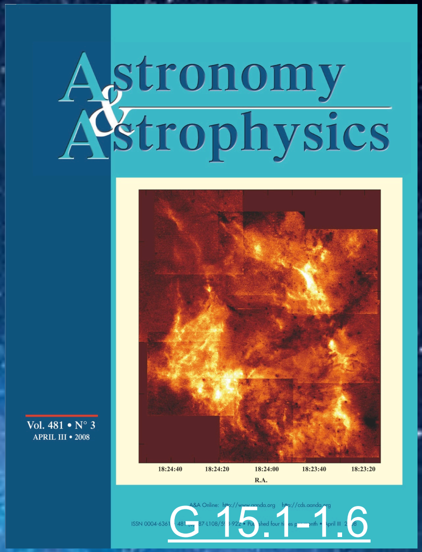
There are 2 types of supernova:

- Type Ia SN, which result from a binary system (white dwarf and a red giant companion).
- Core-collapse SN (Type II, Type Ib, Ic), which result from the explosion of a massive star.



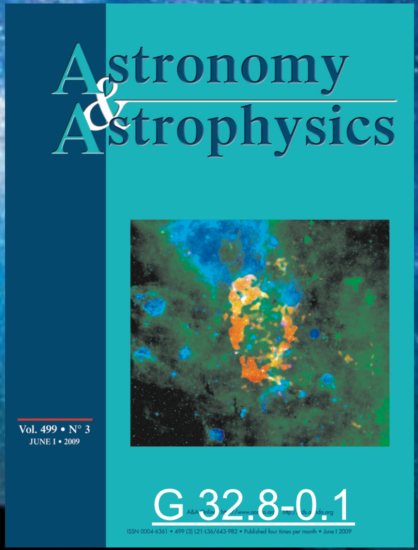
SNRs characteristics:

- Total explosion energy ~$10^{47\text{-}52}$ erg.
- Mass loss ~10^{-1}-10 M_{sun}.
- Velocity of the shell ~3000-10000 km/s.



G 15.1-1.6

Boumis et al. 2008



G 32.8-0.1

Boumis et al. 2009

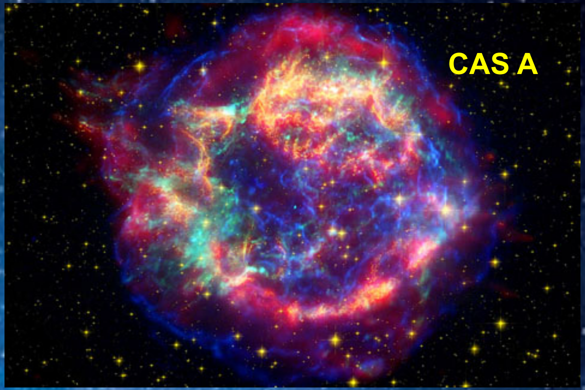
Supernova Remnants

There are three types of supernova remnant:

- Shell-like, such as Cassiopeia A
- Composite, in which a shell contains a central pulsar wind nebula, such as G11.2-0.3 or G21.5-0.9.
- Mixed-morphology remnants, in which central thermal X-ray emission is seen, enclosed by a radio shell, such as W28 and W44.

The evolution of SNRs is usually divided in four phases:

(I) the ejecta dominated phase (*Mej* > *M*sw).
(II) the Sedov–Taylor phase (*M*sw > *M*ej).
(III) the pressure-driven, or “snow-plough” phase (radiative cooling has become energetically important).
(IV) the merging phase (the shock velocity and temperature behind the shock become comparable to the turbulent velocity and temperature of the ISM.



This image combines images from The *Hubble Space Telescope* (HST), the *Chandra X-ray Observatory* (CXO), and the *Spitzer Space Telescope* (SST).

Supernova Remnants

Why are SNRs important?

- They are useful tools of stellar evolution (stellar models)

- They play an important role in the chemical enrichment of the interstellar medium (distribution of abundances in our Galaxy). So, we can study how the ISM evolves as a result of the interaction between the shock wave and the ISM.

- We can study the interaction of the shock wave with the interstellar dust (in the infrared) and provide information of star-forming regions so, its attenuation and extinction effects on starlight can be measured, giving us an idea of how much dust is in the universe.

- They are considered the major source of galactic cosmic rays, since they can provide the energetic shock fronts required to generate high-energy cosmic-rays (up to 10^{18} eV).

Planetary Nebulae – KjPn 8

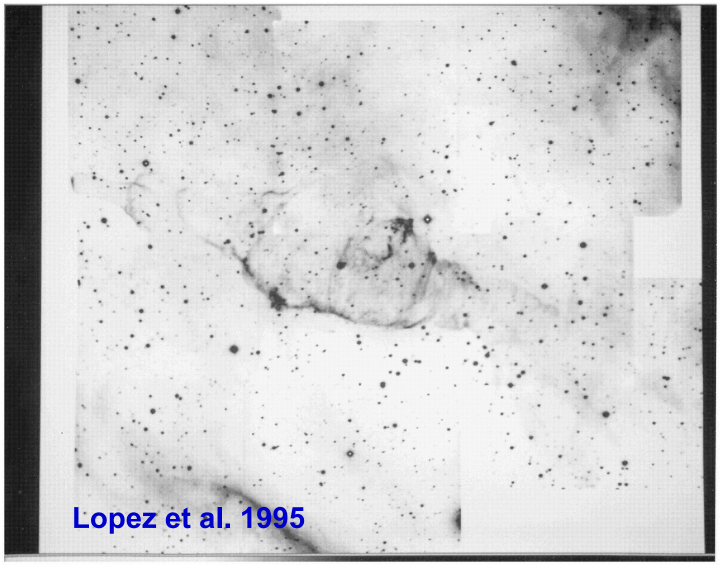
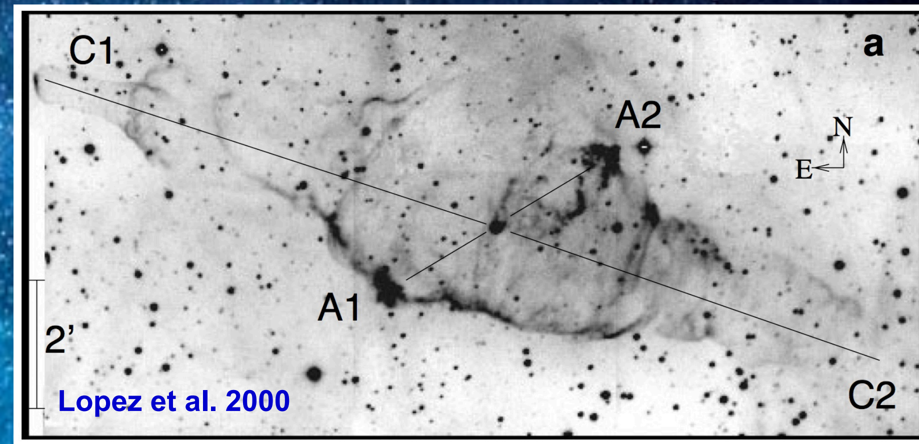
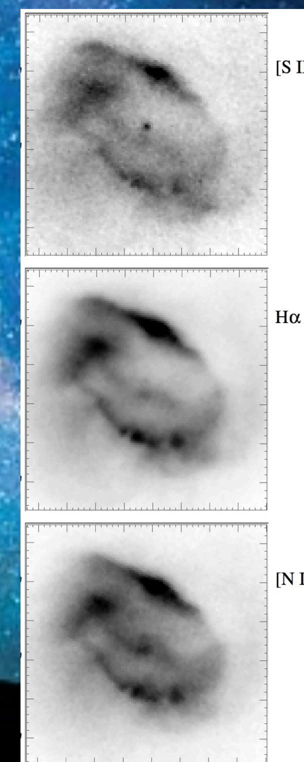


FIG. 1.—Hα mosaic of KjPn 8 composed of nine 1024^2 frames and covering the full extent of the bipolar envelope. North is up, and east is to the left. Each CCD frame is 5′.12 on its side.

LÓPEZ, VÁZQUEZ, & RODRÍGUEZ (see 455, L63)





- KjPn 8 is a polypolar PN with a large-scale structure (14' x 4').
- Bipolar ejections in changing direcitons have occurred to create this peculiar nebula.
- HST images revealed the central star, its type is still unknown and there is a young elliptical ring (4" x 2") expanding at only 16 km/s.
- The ring is the ionized inner region of a larger molecular CO (Forveille et al. 1998 and H2 (Lopez et al. 1999) counterparts.

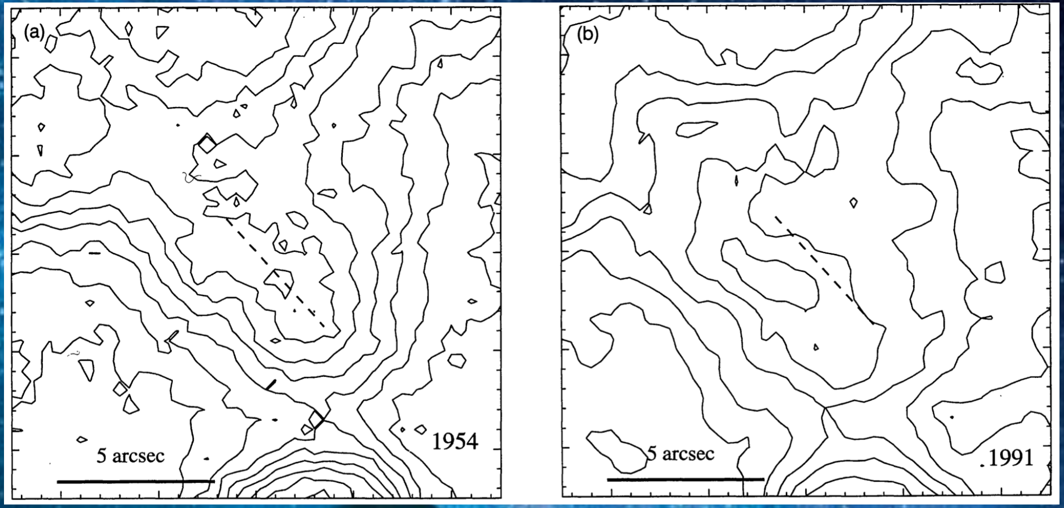
Planetary Nebulae – KjPn 8

Meaburn 1997, MNRAS, 292, L11
37 years interval

$\theta = 37°$ and $V_t = 251 \pm 20$ km s^{-1}

$\mathrm{PM} = 34 \pm 3$ mas yr^{-1}

$D\,(\mathrm{pc}) = 0.2168\ V_t(\mathrm{km\ s^{-1}})/\mathrm{PM}\,(\mathrm{arcsec\ yr^{-1}})$



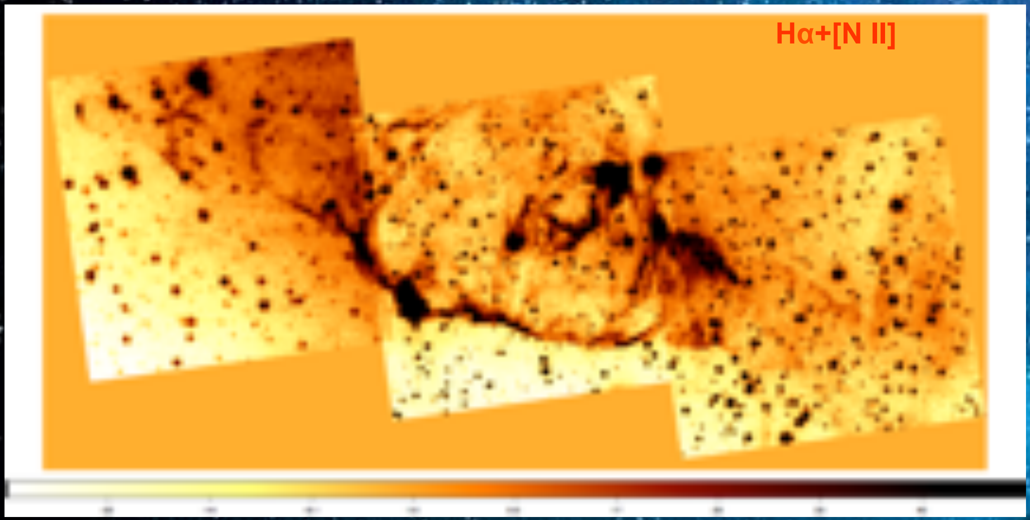
- The EPM of A1, A2 high speed knots has been measured to ~34 mass/yr by comparing the POSS 1954 and 1991 plates (displacement = 1.25”).
- The expansion velocity has been calculated by using the radiative bow-skock model of Hartigan et al. 1987.

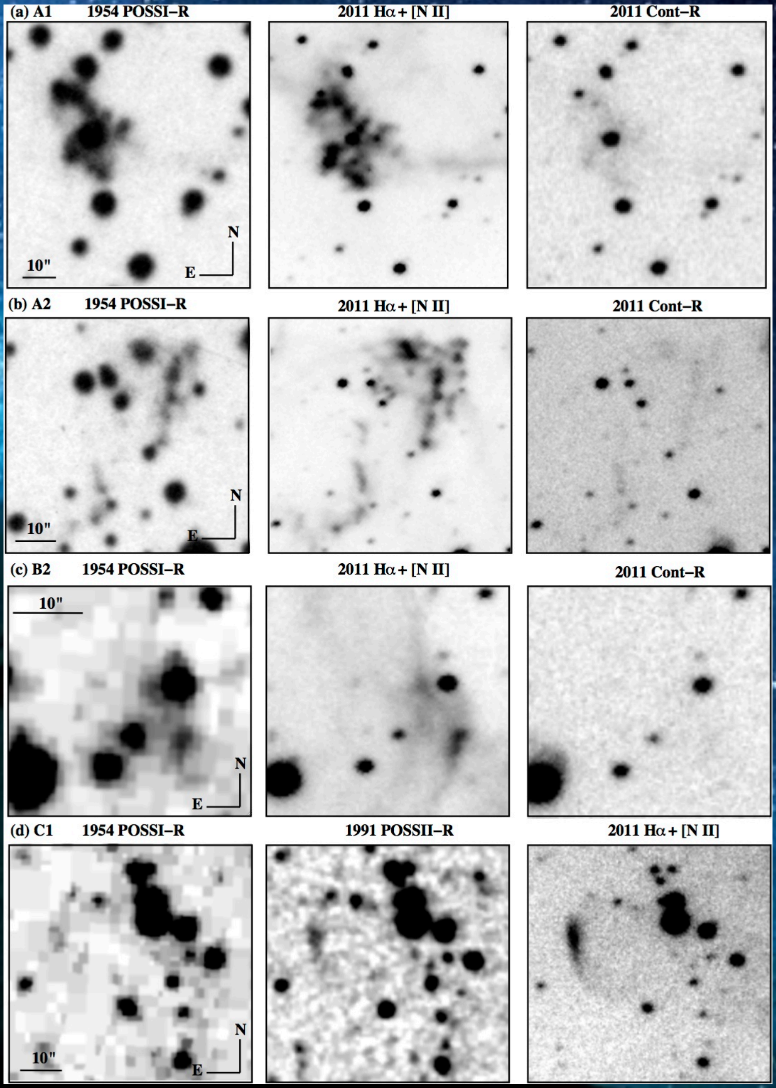
$D = 1600 \pm 230$ pc

$T = 3400 \pm 300$ yr

Planetary Nebulae – KjPn 8

Boumis & Meaburn 2013, MNRAS, 430, 3397

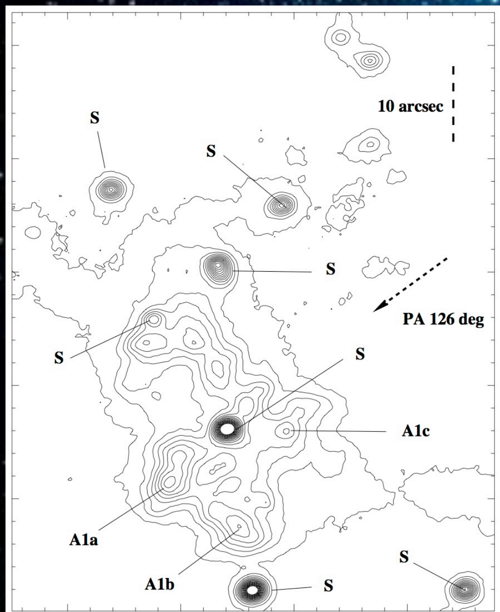




57 years interval

Planetary Nebulae – KjPn 8

Boumis & Meaburn 2013, MNRAS, 430, 3397



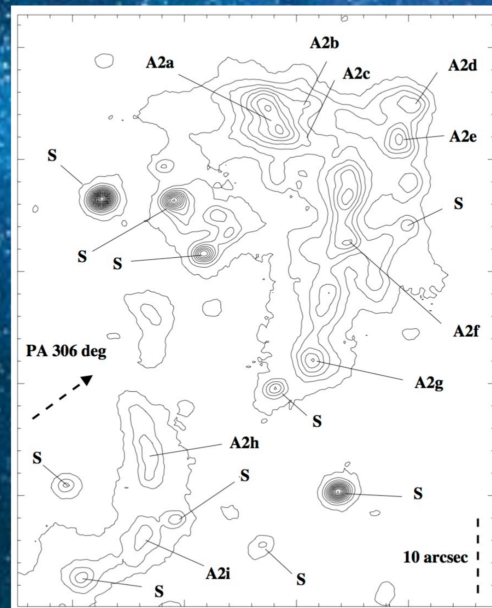
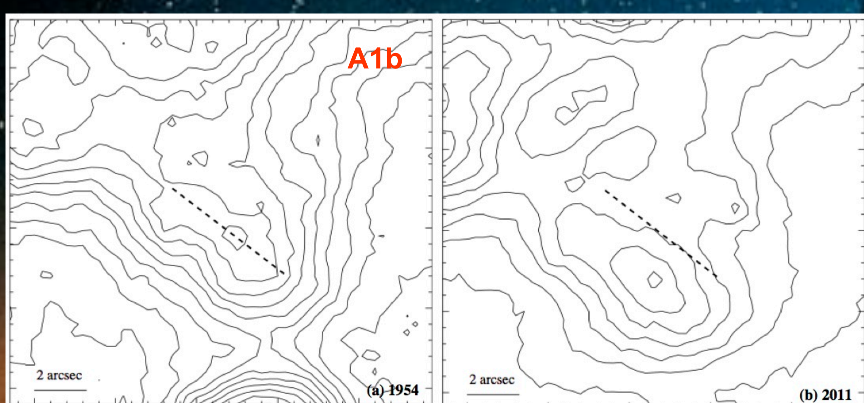
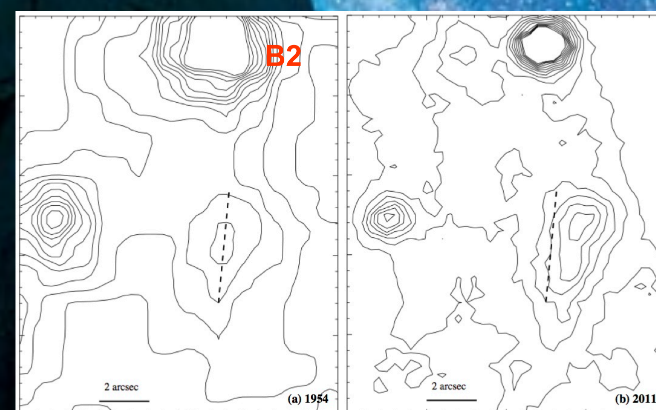


Table 1. In column 1 the ionized knots identified in Figs 1(a), 3 and 4 are listed. Their EPMs and position angles (PAs) of their motions since 1954 are given in columns 2 and 3, respectively. The rates of these expansive motions over the 57 yr between observations and their distances from the central star are given in Columns 4 and 5, respectively. These rates and distances are converted into dynamical ages in column 6. The percentage errors listed in column 2 pass through to the values in columns 4 and 6.

Knot parameters					
Knot	EPM (arcsec)	PA (°)	EPM rate (mas yr^{-1})	Separation (arcsec)	Dynamical age (yr)
A1a	2.05 ± 0.3	146	35.9	118	3284
A1b	1.77 ± 0.2	136	31.6	115	3630
A1c	2.85 ± 0.5	147	50.0	106	2116
A2a	2.40 ± 0.5	317	42.1	110	2606
A2b	1.77 ± 0.3	306	30.5	116	3810
A2c	2.13 ± 0.3	306	37.4	114	3035
A2d	2.30 ± 0.3	315	40.4	126	3121
A2e	–	–	–	124	–
A2f	1.80 ± 0.3	300	31.6	111	3525
A2g	1.54 ± 0.3	293	27.2	102	3739
A2h	2.96 ± 0.5	10	51.9	78	–
A2i	2.70 ± 0.3	336	47.4	75	1577
B2	1.10 ± 0.3	290	19.3	139	7218
C1	≤ 0.5	–	–	423	$\geq 5 \times 10^4$





distance to KjPn 8 of 1.8 ± 0.3 kpc

3200, 7200 and $\geq 5 \times 10^4$ yr

Planetary Nebulae – KjPn 8

Boumis & Meaburn 2013, MNRAS, 430, 3397

IS THIS PN FORMED IN AN ILOT EVENT?

Intermediate-Luminosity Optical Transients (ILOTs) are erupting objects with peak luminosity (M_V~12 and 13) between novae and supernovae (Bond et al. 2009 in NGC 300). These outbursts are powered by mass accretion onto a main-sequence companion from an AGB star.

- Characteristics of ILOTs in PNe (Soker & Kashi 2012):

1. Bipolar structure
   YES
2. Expansion velocity of a few x 100 km/s
   Vt=334 km/s
3. Total kinetic energy of ~ 10^{46} – 10^{49} erg
   KE~10^{47} erg
4. Linear relation between velocity-distance (of the PN component that ejected during the ILOT event.
   YES

All are comparable to those of the polypolar PN NGC 6302, which led Soker & Kashi (2012) to suggest and Intermediate-luminosity optical transient (ILOT) origin.

Planetary Nebulae – KjPn 8

Boumis & Meaburn 2013, MNRAS, 430, 3397

CONCLUSIONS

- The EPM rates of the A1 and A2, B2 and C1 giant lobes are measured as 33.9, 19.3 and <8.8 mas/yr. The dynamical ages of these features are then 3200, 7218 and > 5 x 10^4 yr.

- The outflow velocity of the A1 and A2 bilopar lobe is 334 km/s

- A distance D to KjPn 8 is derived as 1.8 Kpc. This has been derived by combining the EPM rate of the A1 and A2 outflow, for several unresolved knots.

- If the youngest and most energetic A1 and A2 lobes, originated in an ILOT event, a candidate for the massive AGB star that is required could be the compact radio source in the central nebula. Any evidence that this is a binary system should be investigated.

- The older C1, C2 and B1, B2 lobes could have been generated by less energetic ejections, from the same binary system, that preceded the final ILOT event. The binarity could also explain the different directions of the ejections.

Planetary Nebulae – Helix Nebula

NGC 7293 is an evolved PN very close to the Sun (219 pc – Mendez et al. 1988)

Observations of the morphology and kinematics of many of the structures up to diameter of 25’ have been made on a variety of spatial scales (Meaburn, Boumis et al. 2005, Meixner et al. 2005, Matsuura et al. 2009, Meaburn & Boumis 2010, O’Dell et al. 2004 & 2007 etc.).

Deep optical imaging revealed what appeared to be a bow-shock and a jet in the very outer 40’ diameter faint halo of NGC 7293 (Meaburn, Boumis et al. 2005).

Meaburn, Boumis et al. 2005

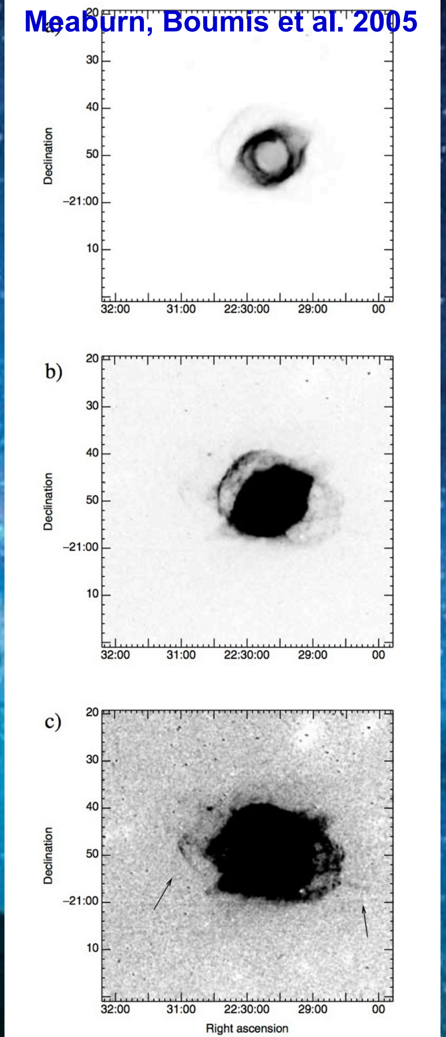
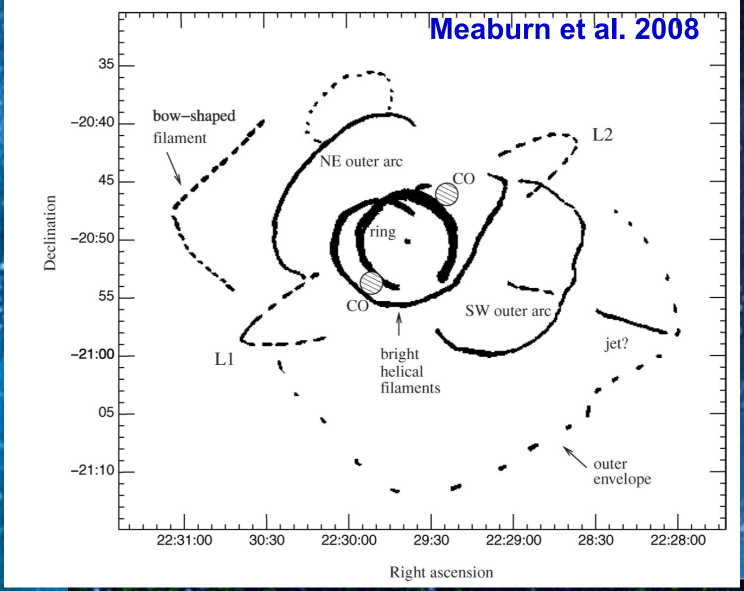


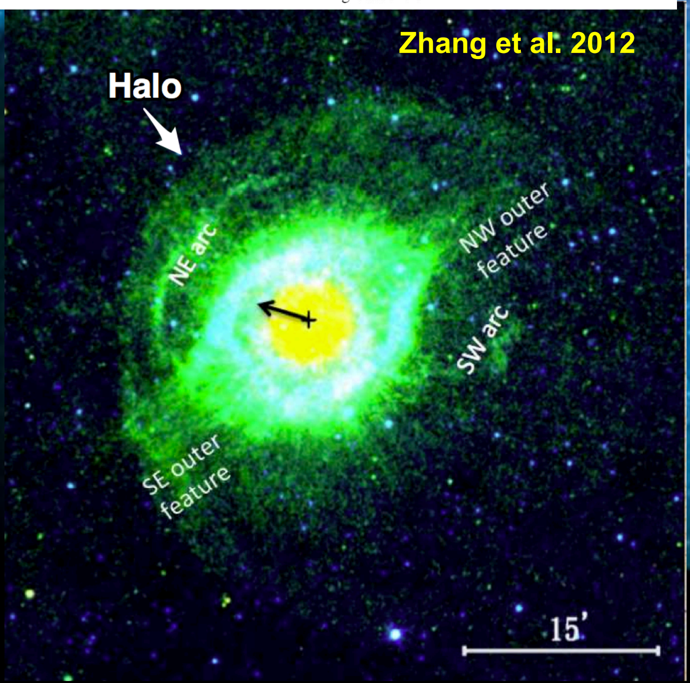
Figure 1. The same deep Hα+[N II] image is displayed at three contrast levels to show all of the features from the bright, inner helical structure out to the very faint halo regions (epoch 2000). The bow-shaped feature and jet-like feature are both indicated with an arrow in (c).

Planetary Nebulae – Helix Nebula

Both features were subsequently detected in the GALEX NUV (175-280 nm) images (Meaburn et al. 2008) where the edge of this halo was called “outer envelope”.



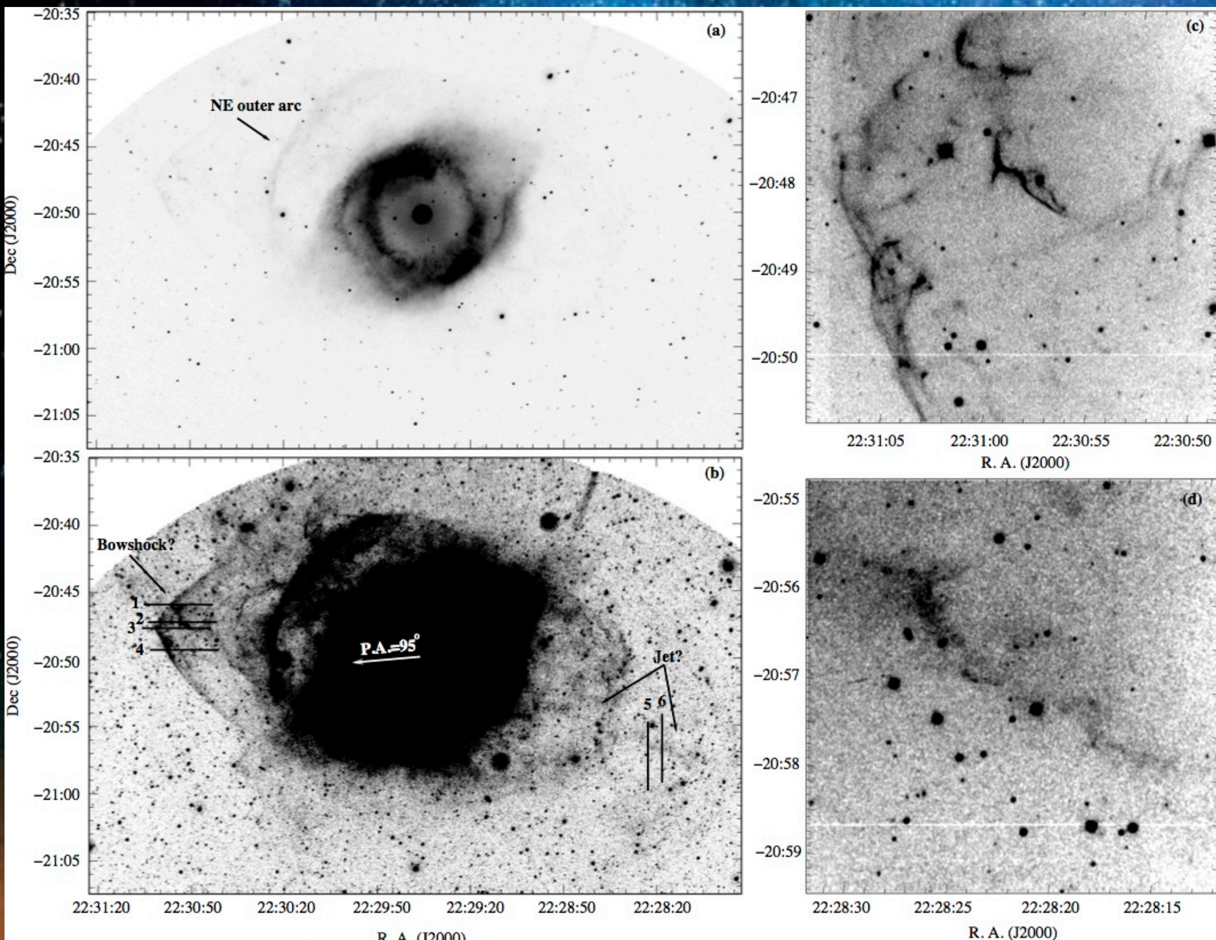
Recently, they have also be seen in the WISE image of NGC 7293 at 12μm (Zhang et al. 2012).

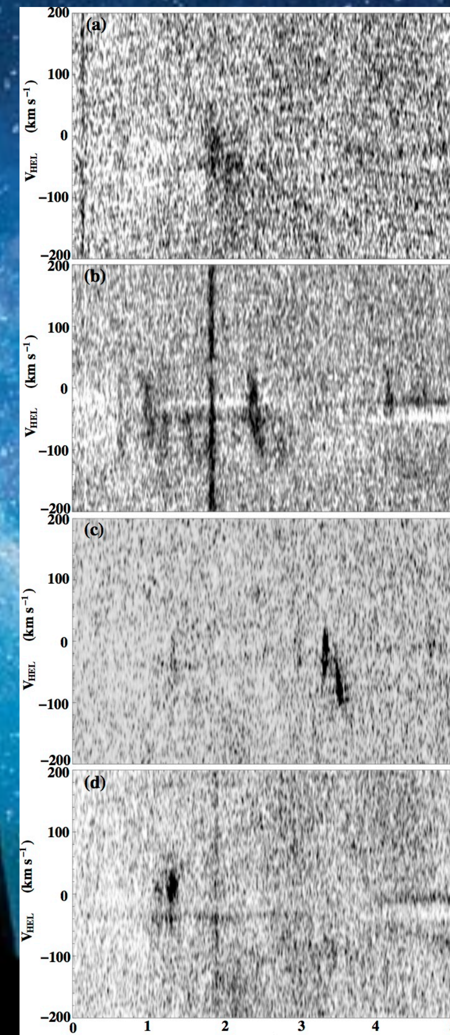


Planetary Nebulae – Helix Nebula

Meaburn, Boumis & Akras 2013, MNRAS, in press

The GALEX NUV (175-280 nm)   Hα+[N II] - Aristarchos telescope   Hα echelle spectra – SPM telescope





The new kinematics and imaging data helped us to determine the origin of the bowshock and jet-like structures.

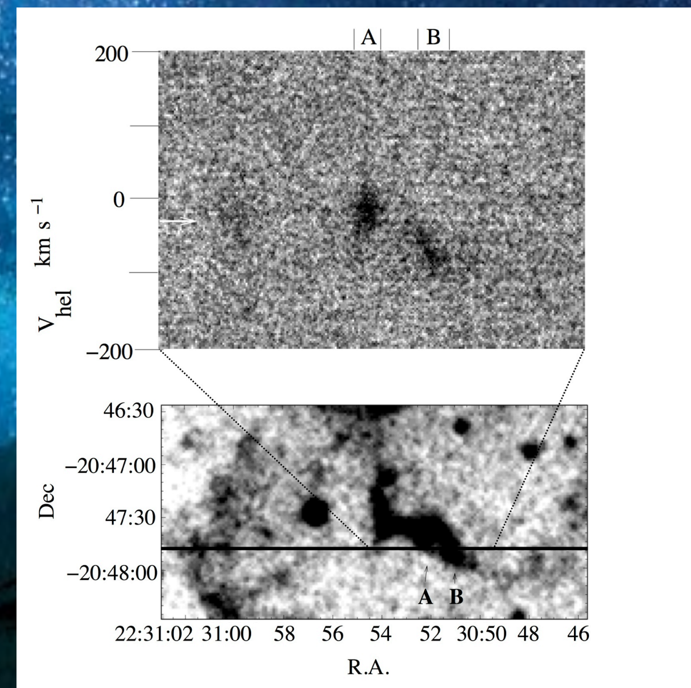
Planetary Nebulae – Helix Nebula

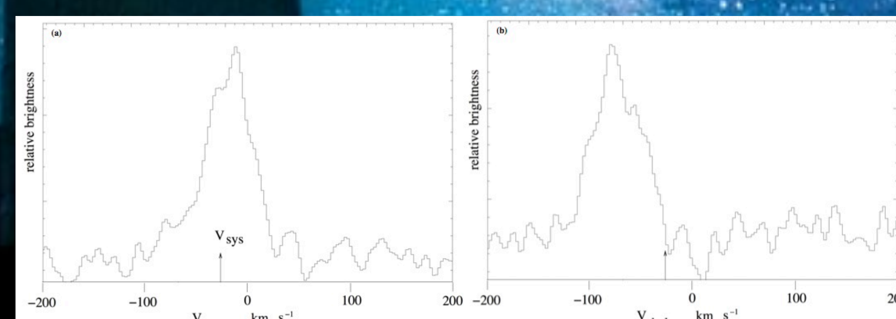
Meaburn, Boumis & Akras 2013, MNRAS, in press

CONCLUSIONS (1)

The bow-shock is caused by the motion of NGC 7293 as it ploughs through this medium since:

- It cannot be ahead of a counter jet to the SE one since (a) it was not detected and (b) the velolicties are <100 km/s.
- The bow-shock structure has Hα radial velocity close to the systemic, -27 km/s, of NGC 7293.
- It is faint in the [N II] lines.
- The FWHM of these profiles matches the relative motion of NGC 7293 with its ambient ISM.
- This interpretation is also consistent with the direction of the PM of the CS.





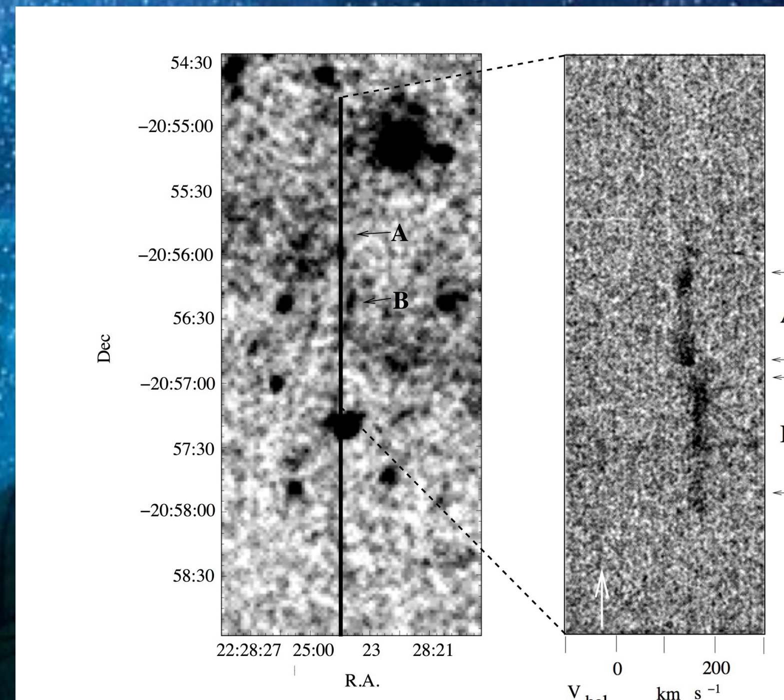
Planetary Nebulae – Helix Nebula

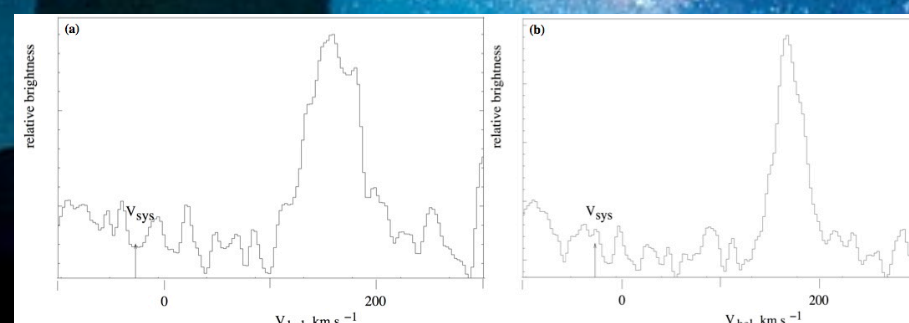
Meaburn, Boumis & Akras 2013, MNRAS, in press

CONCLUSIONS (2)

The jet-like feature is confirmed kinematically to have a jet origin since it has:

- a collimated outflow velocity of ~300 km/s.
- a dynamical age T> 6200 yr (which is comparable with the T~10000 yr of the inner emitting CO torus; Young et al. 1999).
- an Hα/[N II] ratio of < 0.2 (which also confirms its origin as collisionally ionized, nitrogen enriched, material from the progenitor star).
- a limited length (8’) of the jet’s outflow (which suggests that it was a short-lived event probably in the early stages as the AGB wind declines and the PN was born).

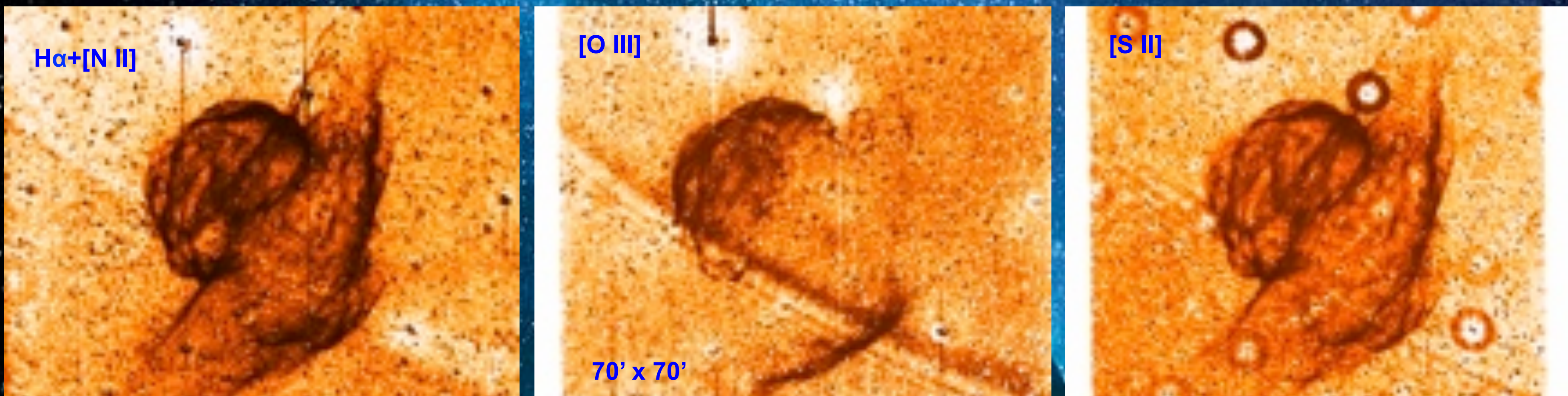




Supernova Remnants – VRO (G 166.0+4.3)

Boumis et al. 2013 (in prep.)

Wide-field imaging - Skinakas telescope

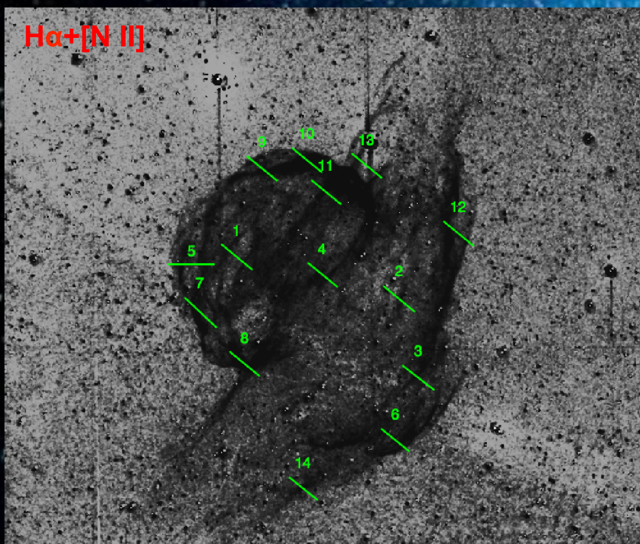


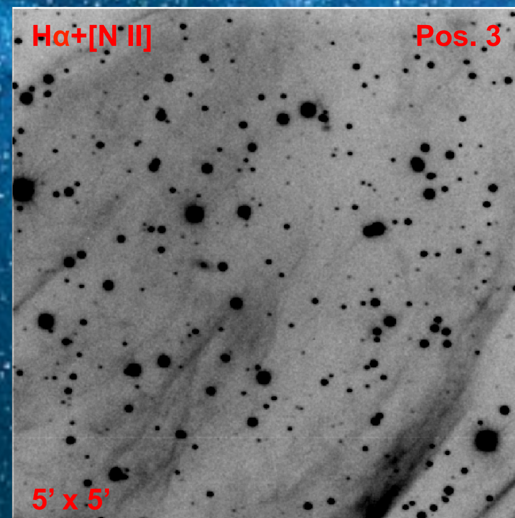
- VRO 42.05.01 is a known SNR (van de Bergh et al. 1973; Fesen et al. 1983, 1985) but because of its large size, it was never studied in detail in the optical band, σo the current stage of its evolution is still unknown.
- It is classified as a shell-type SNR, with a spectral index of ~0.37 (Green 2009).
- Its angular size is 55’x35’
- Using HI measurements the distance of the remnant was calculated at 4.5 kpc (Landecker et al. 1989).

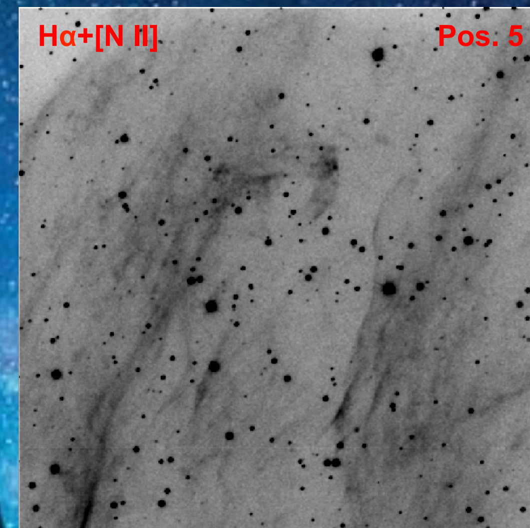
Supernova Remnants – VRO (G 166.0+4.3)

Boumis et al. 2013 (in prep.)

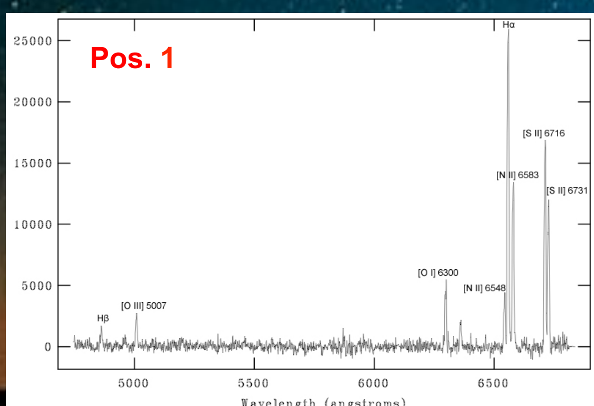
High-resolution imaging - Aristarchos telescope

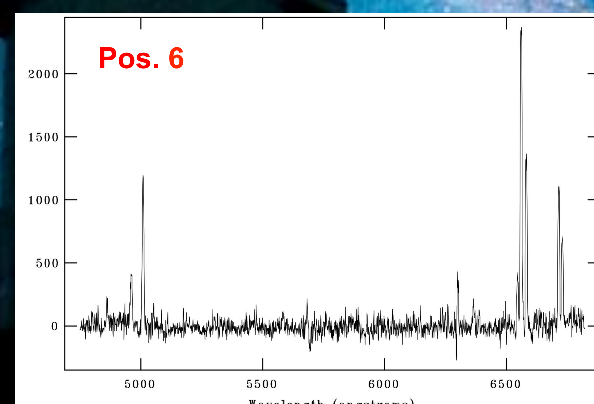






Low-resolution spectra – Skinakas telescope





Supernova Remnants – VRO (G 166.0+4.3)

Boumis et al. 2013 (in prep.)

OBSERVATIONS SUMMARY:

IMAGING:

(a) 0.3m Skinakas tel. Jun & Aug 2005

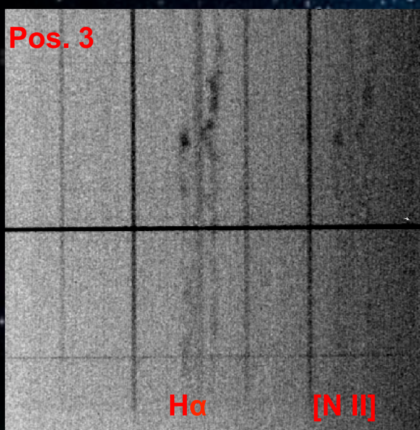
(b) 2.3m Aristarchos tel. Nov 2010

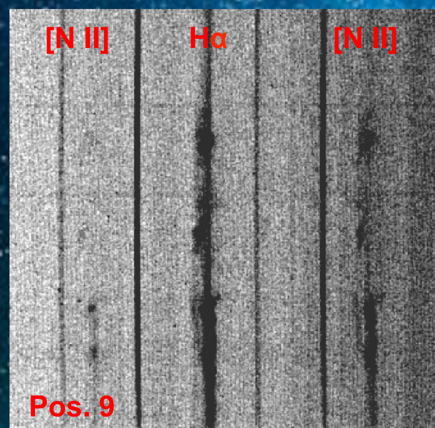
SPECTROSCOPY:

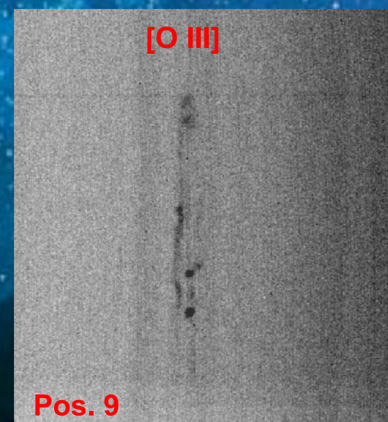
(a) 1.3m Skinakas tel. Aug 2009 & Sep. 2010

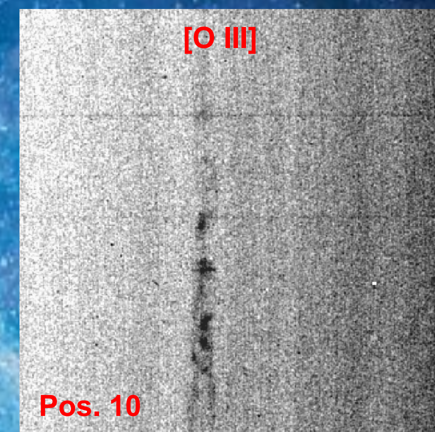
(b) 2.1m SPM tel. Dec 2010 & Nov. 2011, 2012

Echelle spectra – SPM telescope









PRELIMINARY RESULTS:

- The low ionization images show strong filamentary structures which are very well correlated with the radio emission and could be the remnant's outer edge.

- Both the calibrated images and the long-slit spectra suggest that the detected emission results from shock heated gas since the [S II]/Hα ratio > 0.4.

Supernova Remnants – VRO (G 166.0+4.3)

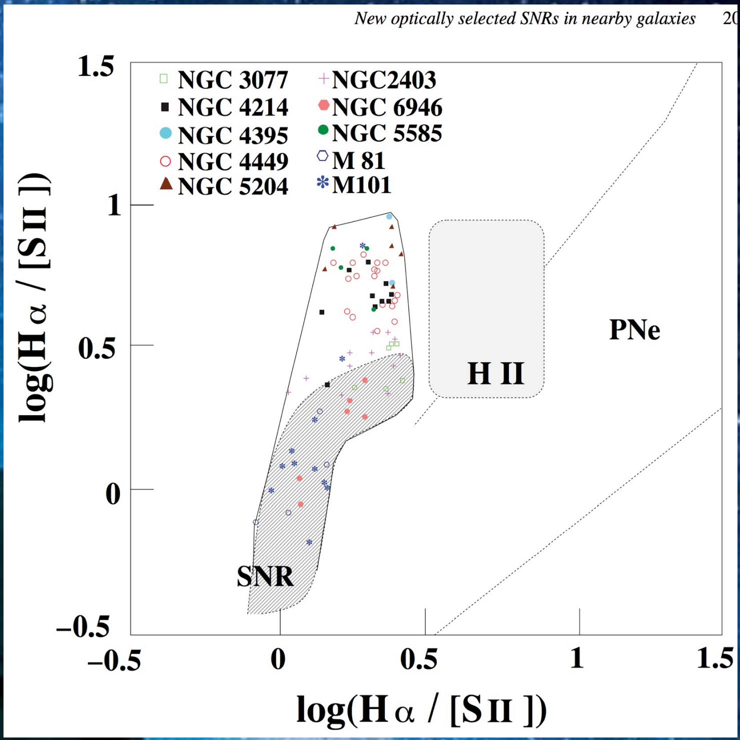
Boumis et al. 2013 (in prep.)

PRELIMINARY RESULTS:

- Diagnostics plots (Leonidaki, Boumis, Zezas 2013, MNRAS,429,189) of the line intensities (log(Hα/[S II]) / log(Hα/[N II]) also confirm that the optical emission comes from an SNR origin and that it is old.

- The electron density was also determined by measuring the density sensitive line ratio of [S II] λλ 6716/6731. The densities we measured are below 240 cm^{-3}.

- The strong [O III] emission detected suggests a shock velocity greater than 100 km s^{-1} (Cox & Raymond 1985).



- Kinematical data are presented for a first time, where velocities up to 150 km/s were measured.

- The large set of data give us the opportunity to discuss in detail its complex morphology.

- Finally, multiwavelength correlation give us a better indication about its evolutionary stage and its interaction with the ISM.