A Deep UV imaging study of the Cygnus SNR.

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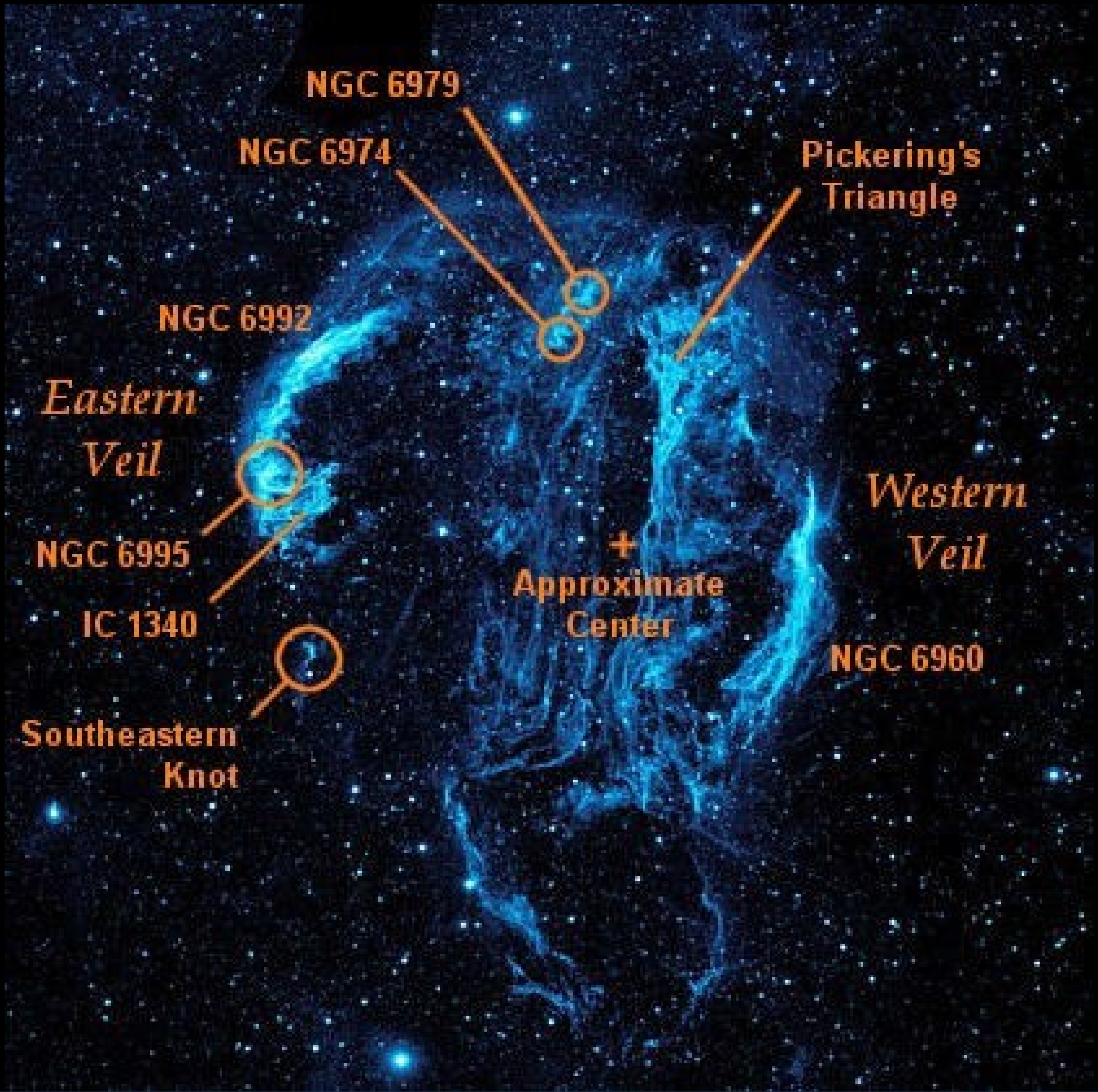


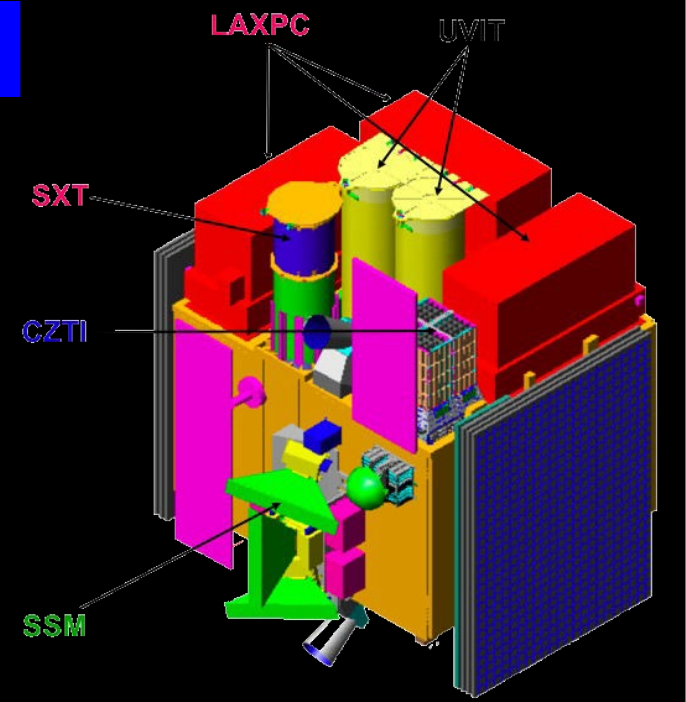
The Cygnus loop in the Galex NUV band. ►

A brief overview of Astrosat

Most relevant instruments for SNR study:

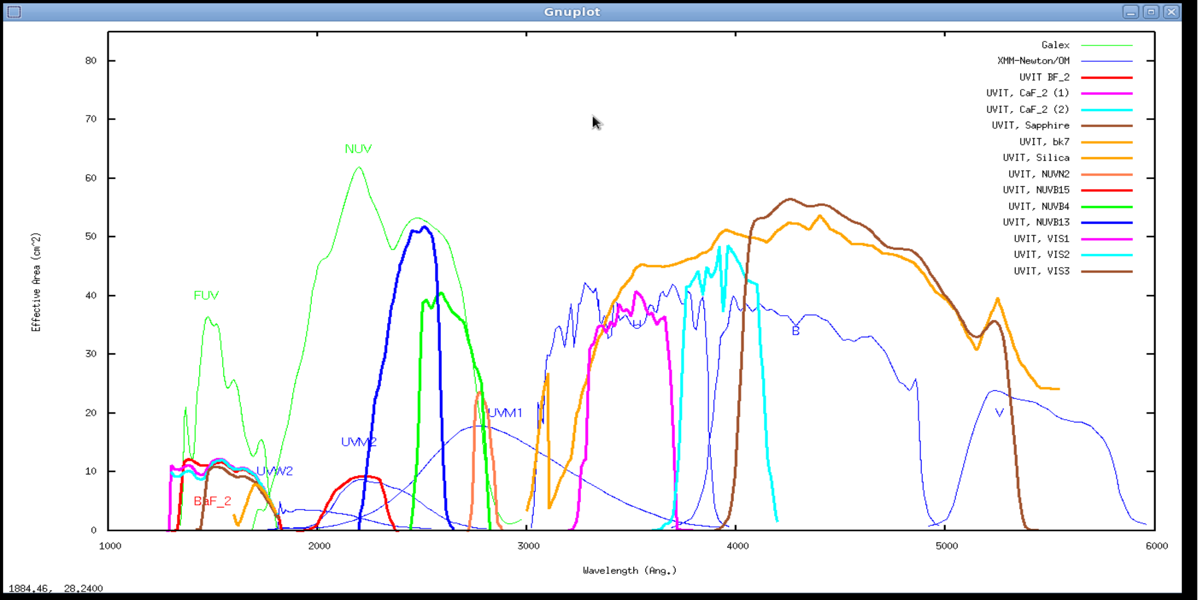
UVIT: FUV / NUV /VIS coverage,
3 channels twin telescope
28’ FoV (FUV/NUV/VIS)
PSF: 1.3” (FUV) and 1.8” (NUV)

SXT: (0.3-8.0 keV), with 40’ FoV and 2’ PSF,
Eff. Area 200 cm^2 at 2 keV (similar to Swift XRT).



▲ Multi waveband (1300 A to 0.1 MeV) space observatory. Developed by TIFR / IIA / ISRO + CSA and U. Leicester. Launched by ISRO in to a near equatorial orbit on October 2015.

F151 (126 - 179 nm)	N242 (194 - 304 nm)
F155 (133 - 183 nm)	N218 (190 - 240 nm)
F161 (145 - 181 nm)	N244 (220 - 265 nm)
F170 (160 - 179 nm)	N263 (250 - 275 nm)
--	N279 (273 - 288 nm)



Why study SNRs? Because they are there!

(SNRs) play a vital role in many area of astrophysics.

- Enrich the ISM with newly nucleosynthesised material from SNe.
- Responsible for the dynamics and kinematics of gas in the ISM, leading to star formation, formation of super bubbles, galactic outflows..
- May be sites for Galactic, ultra-high energy cosmic rays ($E \simeq 10^{14}$ eV), via diffusive shock acceleration in the forward shock.
- Constrain models of late time shock - ISM interaction,
- Provides an insight in to the evolutionary state of the pre-SN progenitor and its CSM.
- Deep (up to Msec) Chandra x-ray imaging of several SNRs highlighted several complex phenomena, both resolving and raising questions about the nature (clumpy, gaseous, or dusty) and the physical properties of the ISM.
- For SNRs that are both optical and X-ray bright, it is important to complement the high temperature (10^{6-7}K) phenomena with UV imaging, sampling regions of 10^{4-5} **K** gas both in filaments and other interacting medium.

The need for UV imaging:

- Narrow band FUV + NUV imaging of hot (10^{4-5} K) and intermediate (5000- 8000 K) regions via emission lines of C IV (1550 Ang.), He II (1640 Ang.), Mg II lines (2800 A) etc., bridges the gap between regions of x-ray bright (10^{6-7} K) and cool, optical regions.

- Ionization states being functions of ρ, μ) ⇒ mapping of thermodynamic conditions within the shocked filaments.

A blast wave that lights up the past

- Core rebound initiates shock wave through progenitor envelope.
- Blast wave propagates out, sweeps up CSM / ISM material in front it.
- Free Expansion phase (10^2 to 10^3 yr):
  Supersonic, adiabatic expansion/cooling, $r_{shock} \propto$ ¿t- 3
- Reverse shock forms at
  $M_{CSM} \simeq M_{ejecta.;}$
  moves inwards, expansion slows, reheating
- Sedov-Taylor expansion (10^4 yr): Adiabatic cooling dominates.
- Snow plow phase: 10^6-10^9 yr
  Radiative cooling dominates.
- Mixing of ISM and ejecta

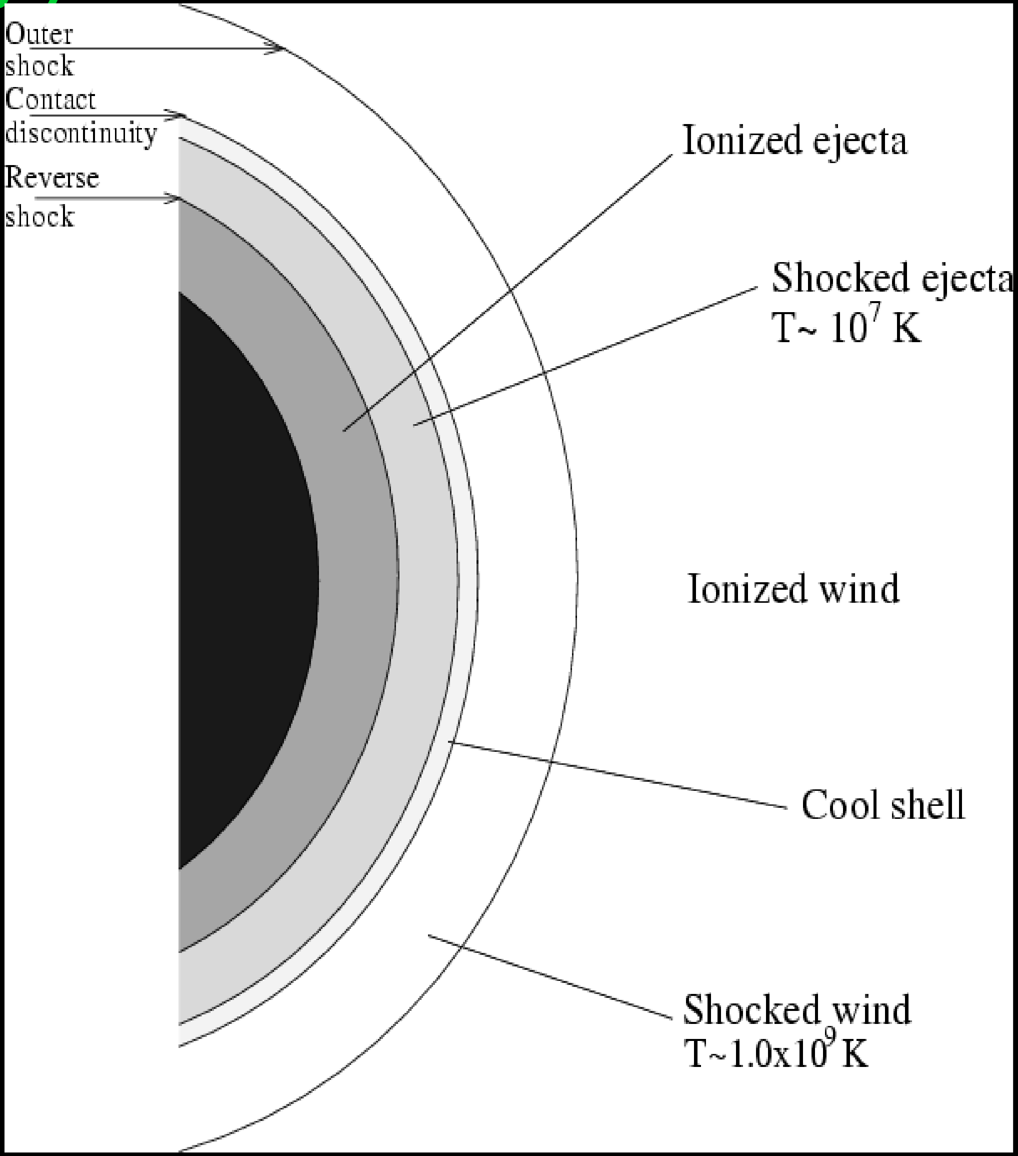


Image credit: Nymark, Fransson & Kozma, 2006, A &A

The Cygnus Loop: an (in)complete picture:

Age: 5000-8000 yr ; distance = 440-770 pc ; R =13 pc at 540 pc.

Morphology:

Extent: $3.5^\circ \times 2.8^\circ$

UV/Optcal: Nearly complete shell;

E(B-V) ~ 0.1 (nearly constant over the SNR extent);

Fragmented in to "filaments", knots, sheets...

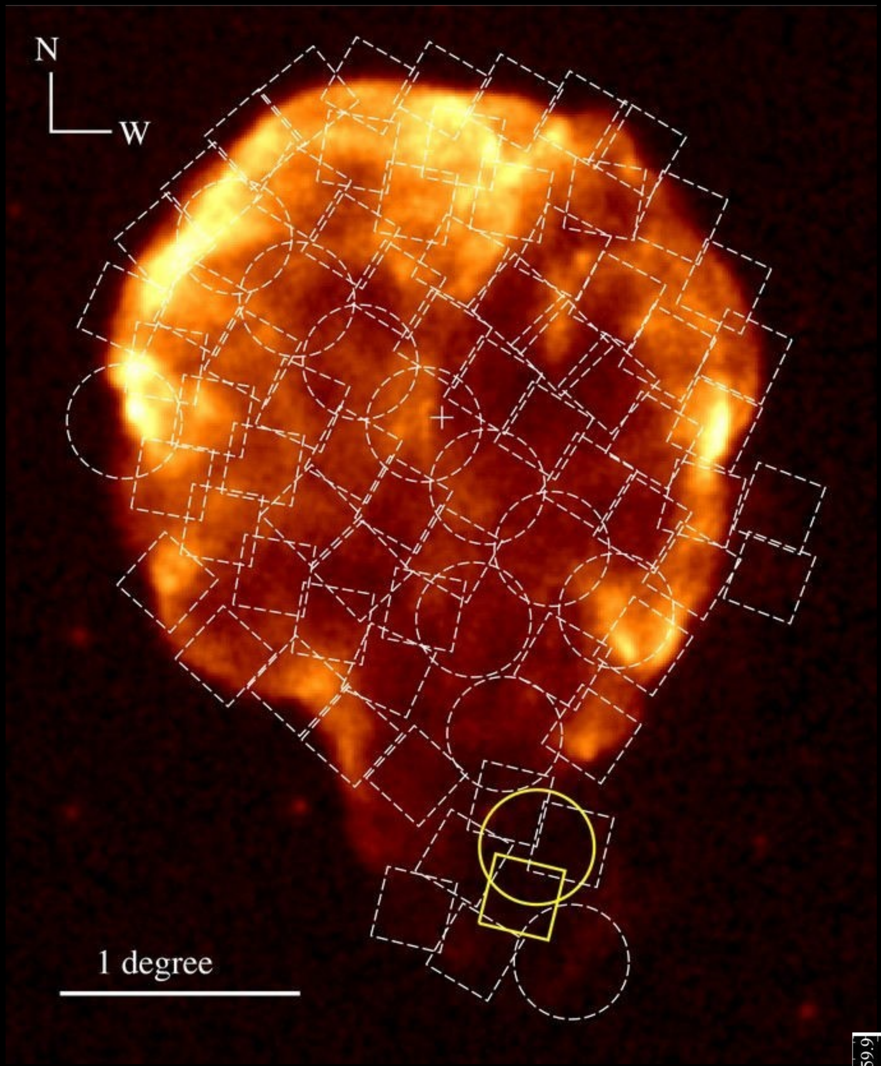
Indicative of a SN blast wave and ejecta running in to the walls of a cavity created by the stellar wind of 15-20 $M_\odot$ B0-B1 or O8-O9 spectral type star [Bohigas et al. 1999, Levenson et al. 1997].

X-ray: ROSAT imaging shows limb-brightened Northern segment dominated by soft thermal emission, but almost no x-ray emission in the South segment

– shock breaks in to a low density region? [Aschenbach & Leahy, 1999]

Radio (2695 MHz): Radio continuum and polarization measurements suggest that the Cygnus SNR may consist of two SNRs – Cygnus N (G74.3 -8.4, $3.0^\circ \times 2.^\circ$) , and Cygnus S (G72.9 -9.0 $1.4^\circ \times 1.8^\circ$). [Uyamker et al. 2002]

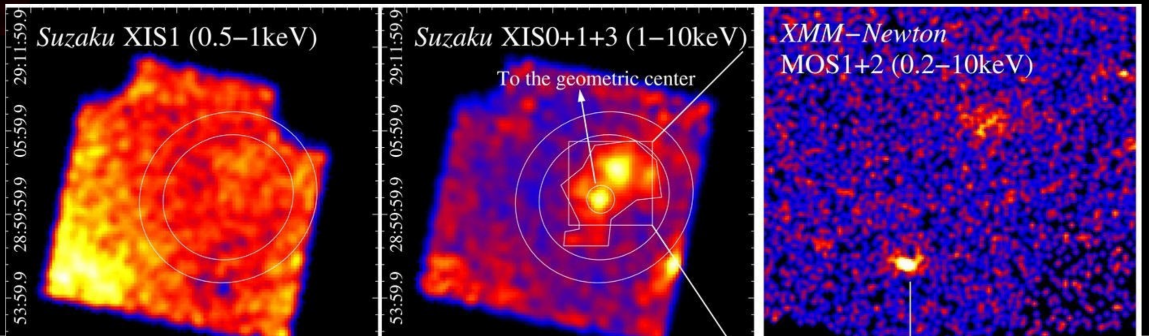
Core-Collapse Event or not?



Hard x-ray source detected in Cygnus South (XMM-Newton and Suzaku survey) best interpreted as PWN [Katsuda et al. 2012], but no pulsations seen.

◄XMM-*Newton* (box) and Suzaku (circle) FoV superposed on ROSAT / ASS 0.2–2 keV image of the Cygnus Loop, scaled as the square root of the surface brightness. The FoV in yellow are shown below. ▼

(l) Vignetting corrected 0.5-1.0 keV XIS1 image,
(c) Vignetting corrected 1.0-10.0 keV XIS0+XIS1+XIS3 image, showing the possible PWN.
(r) 6'x 6' XMM-*Newton* 0.2-10.0 keV FoV localises the proposed PWN.



Cygnus loop – ROSAT PSPC + HRI

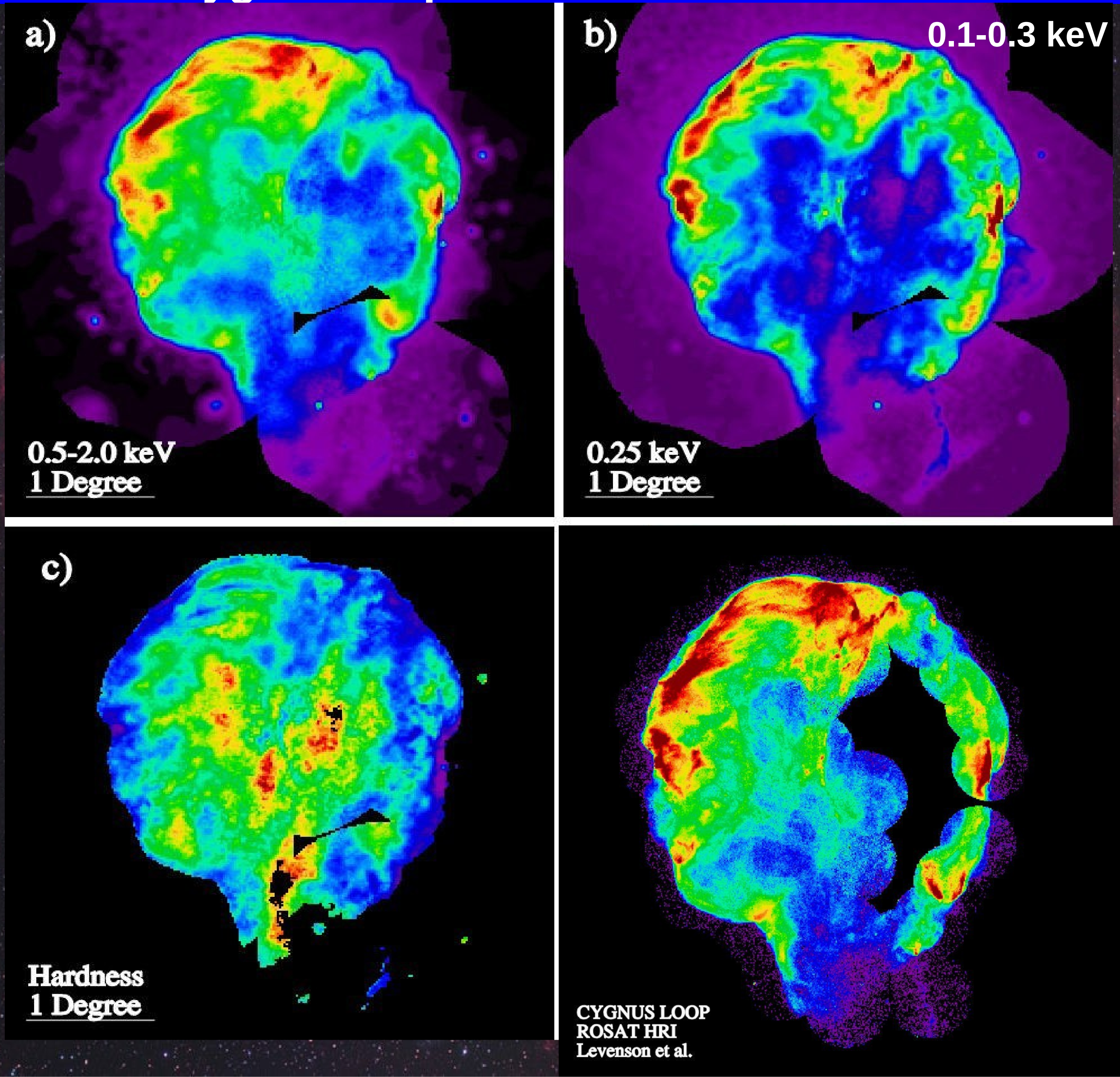
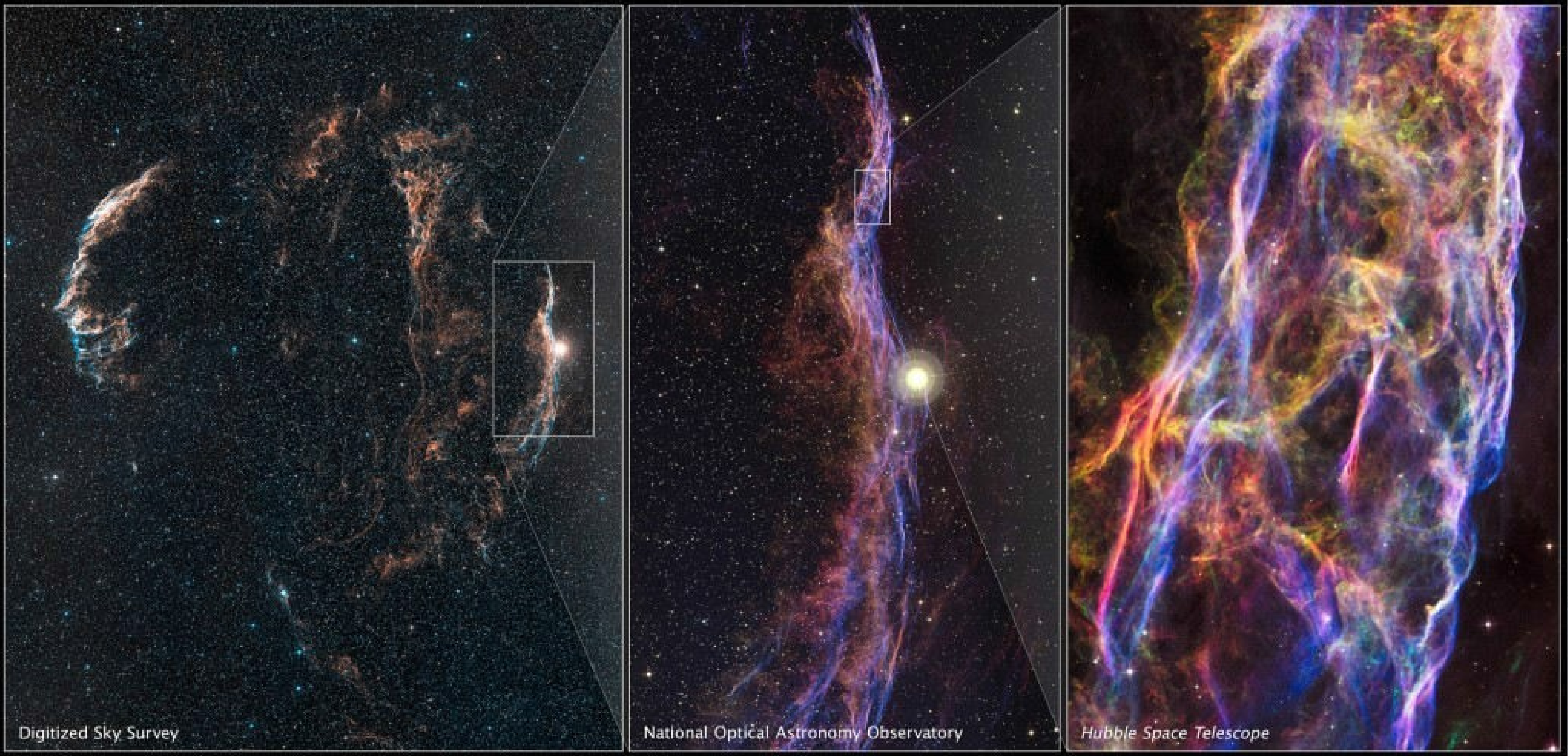


Image Credits: S. L. Snowden and Levensen et al., from ROSAT Gallery

The Cygnus loop in the optical

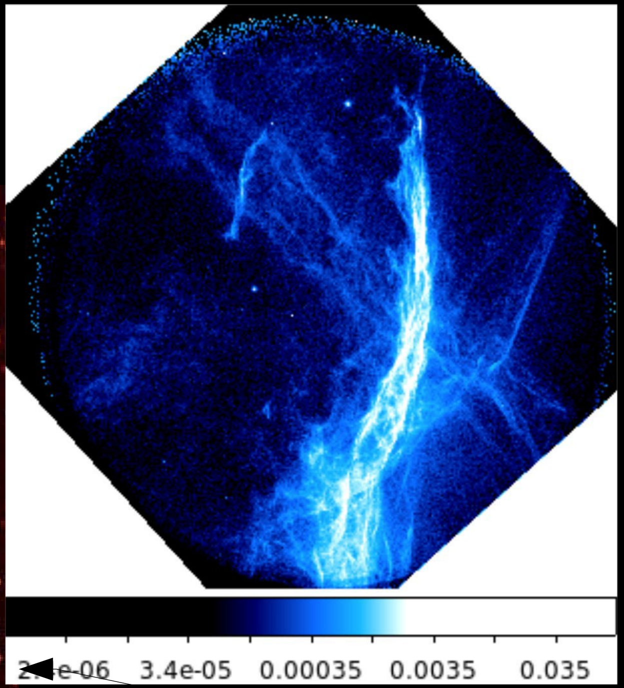


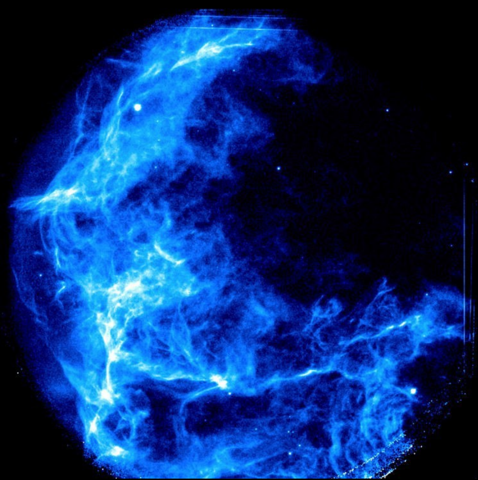
Cygnus Loop and Veil Nebula. Expansion of the nebula has been detected in Hubble images taken between 1997 and 2015, and in Galex Observations taken in 2005
And Astrosat/UVIT observations in 2016-2019.

– [Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), Digitized Sky Survey ((DSS) STScI / AURA, Palomar / Caltech, and UKSTU/AAO), and T.A. Rector (University of Alaska, Anchorage) and WIYN / NOAO / AURA /

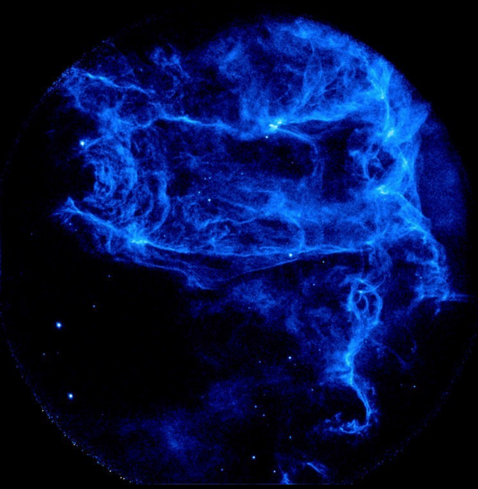
The (planned and observed) UVIT observations:

▼NGC 6960-I (F155)

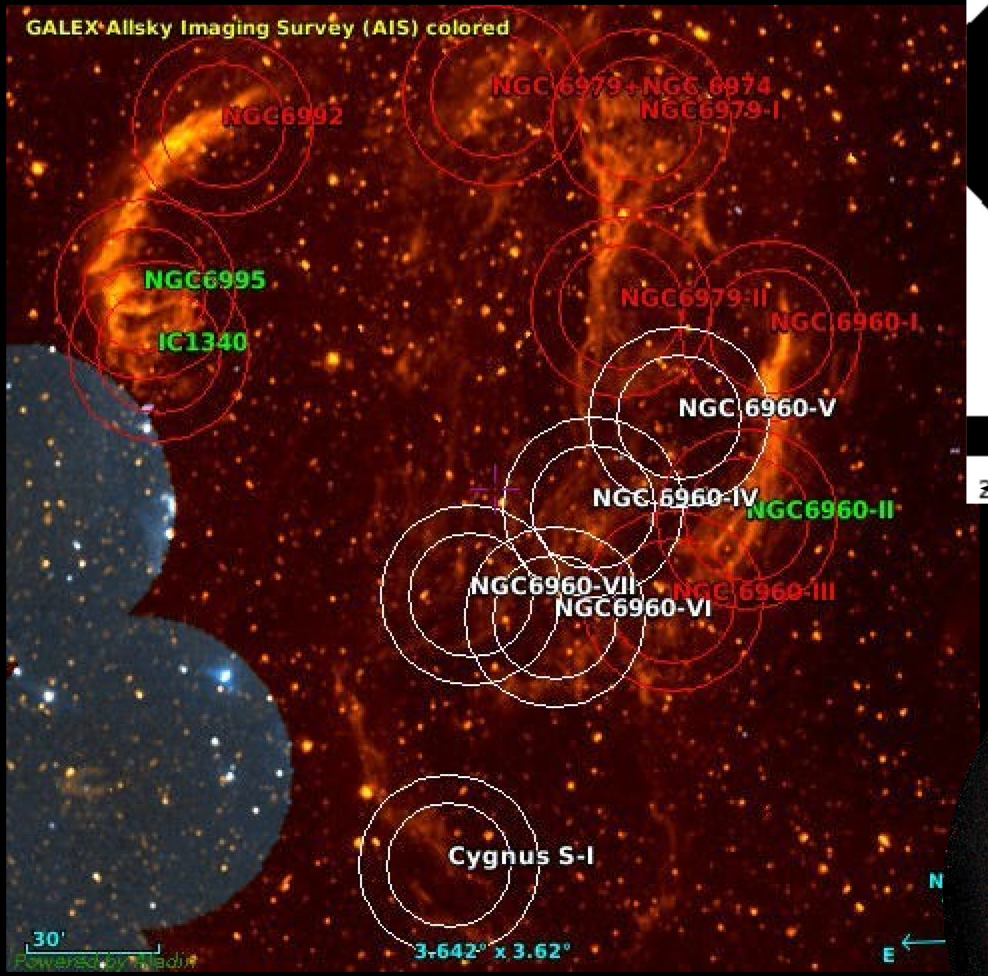




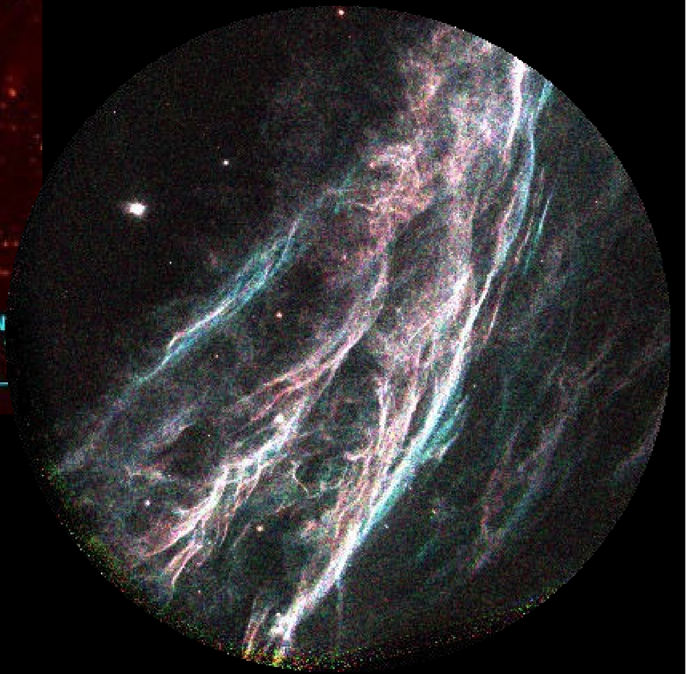
▲NGC6995 (F155)



▲IC1340 (F155)

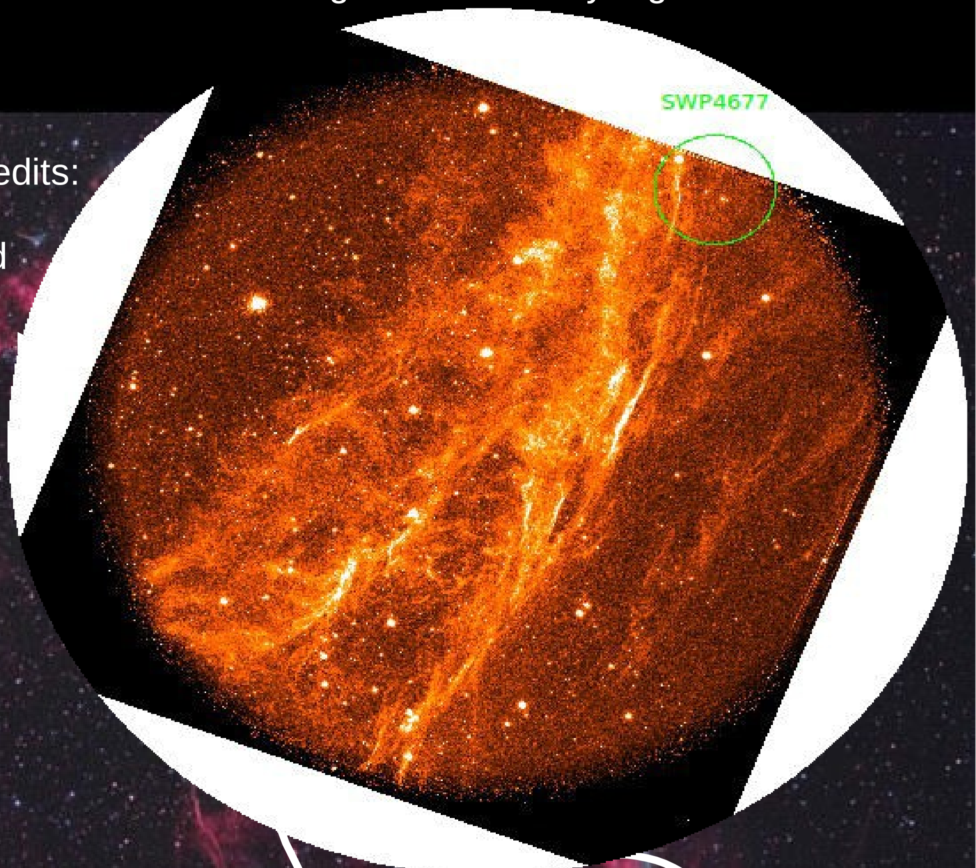


NGC 6960-II ►

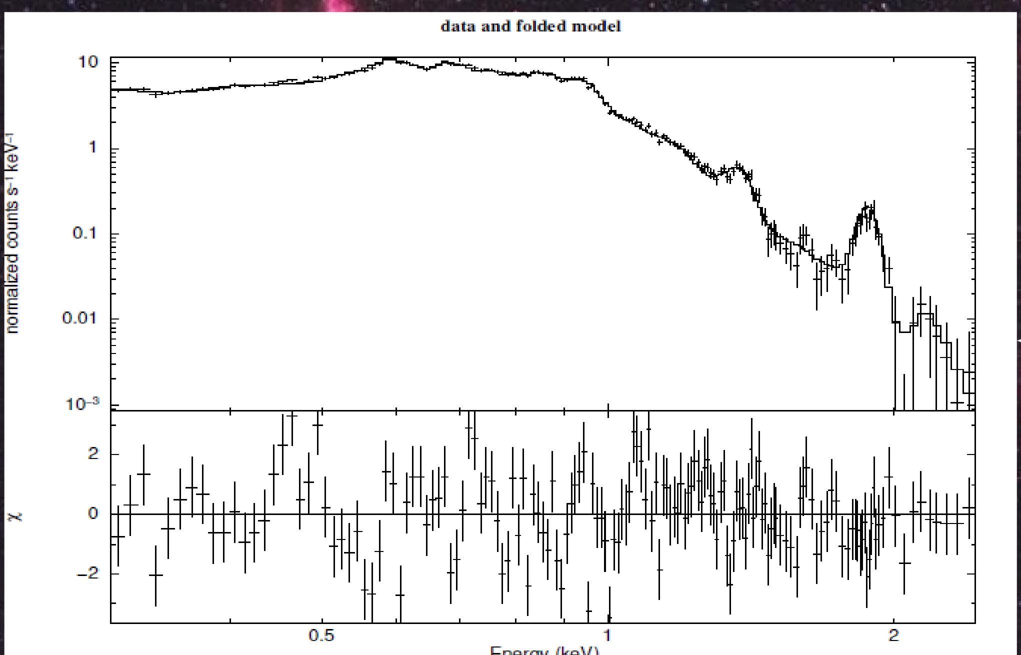


RGB image (F155 + F161 + F170)

▼ N279 image dominated by MgII emission.



UVIT Images credits: Sutaria, Murthy, Singh, Ray, and Rao. Kumar ◄

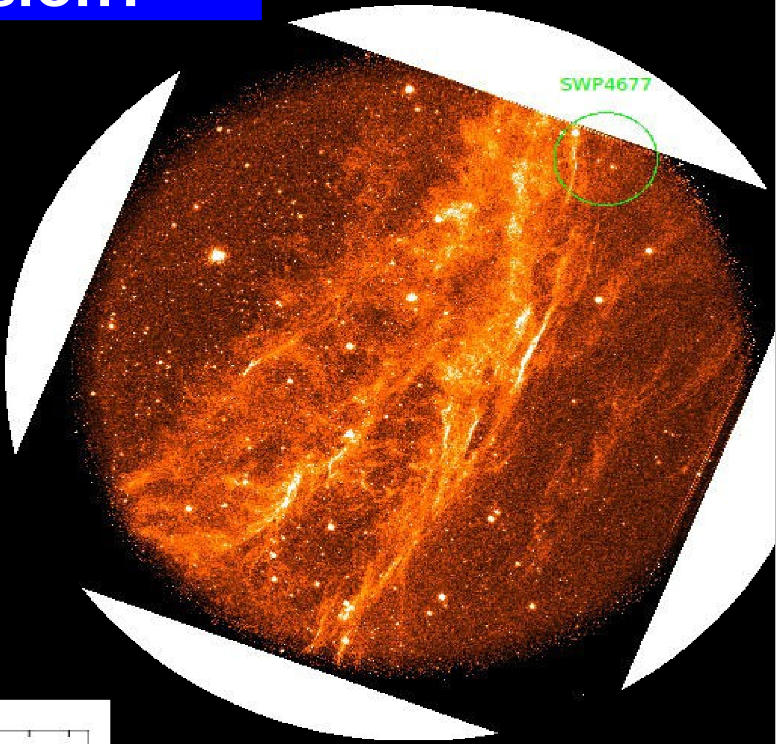


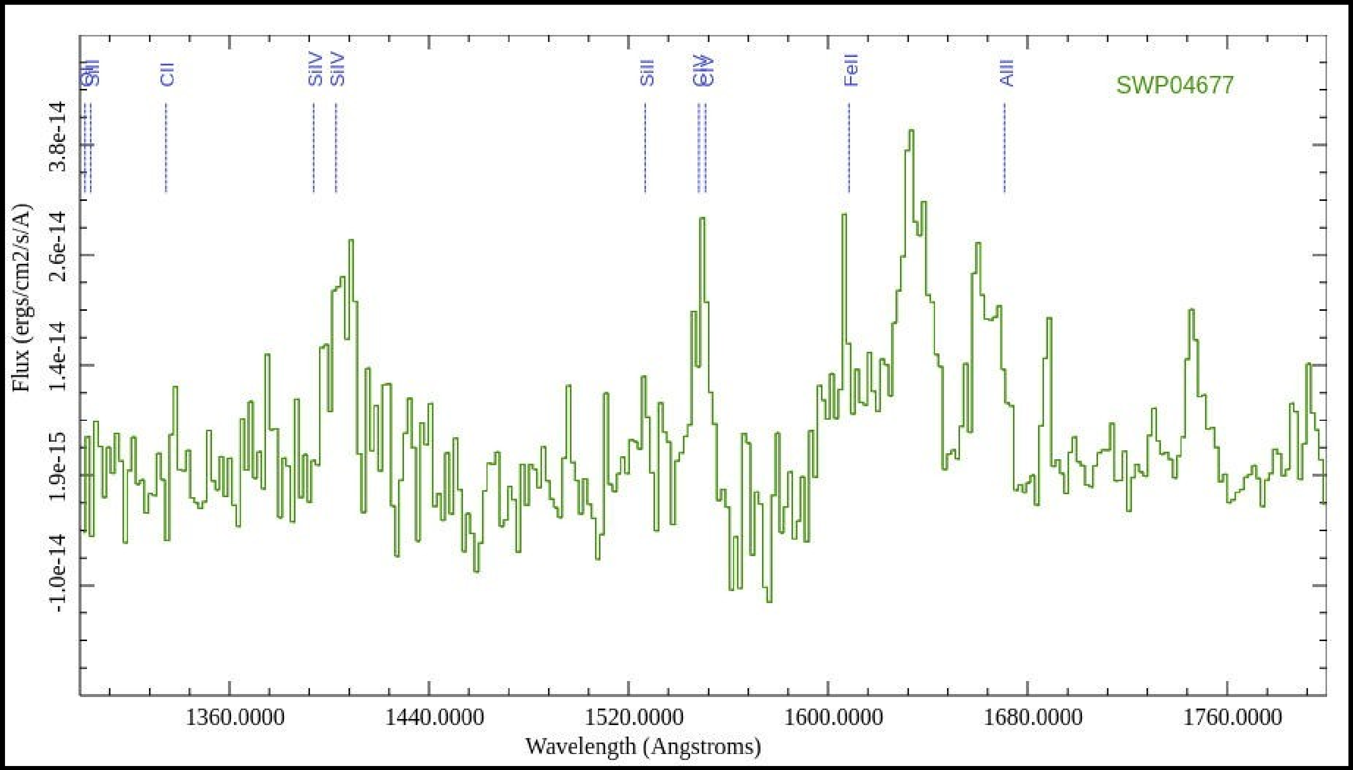
▲Hα + OIII +RVB image Credit: Steve Cannistra.

◄SXT spectrum best fit by two termparure component plasma model **(K. P. Singh, Sutaria , Ray, Murthy, Rao, Kumar).**

What ions are responsible for this emission?

Ionic Species	Wavelength (Angstrom)
Si[II], Fe[II]	[1526.7 ,1532], [1608, 1610]
C[IV]	1548, 1551
Si[IV]	1394, 1403
He[II]	1640



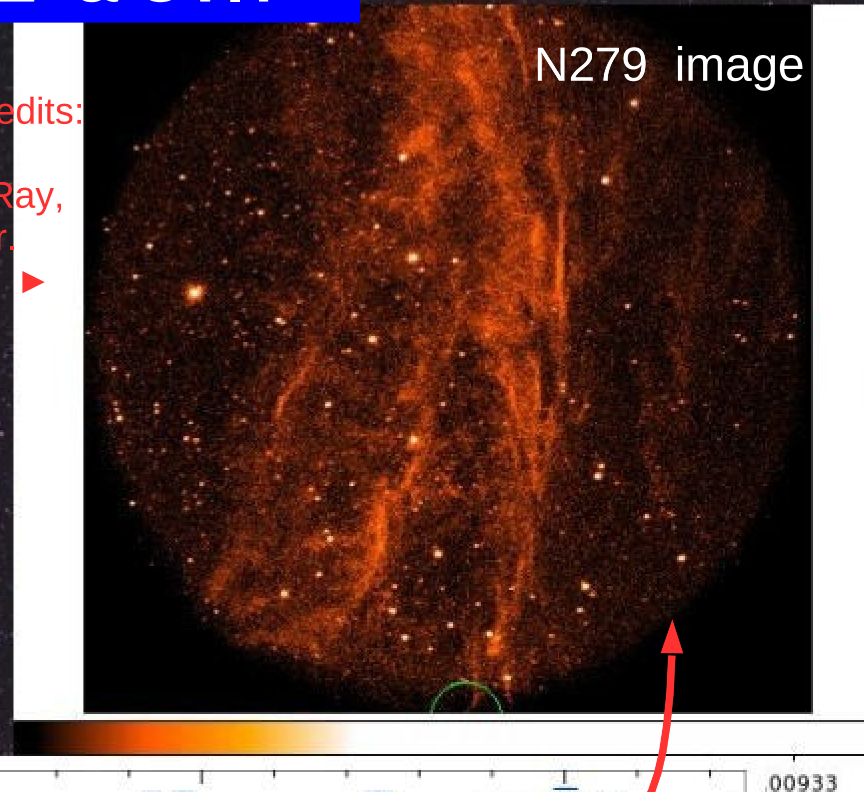


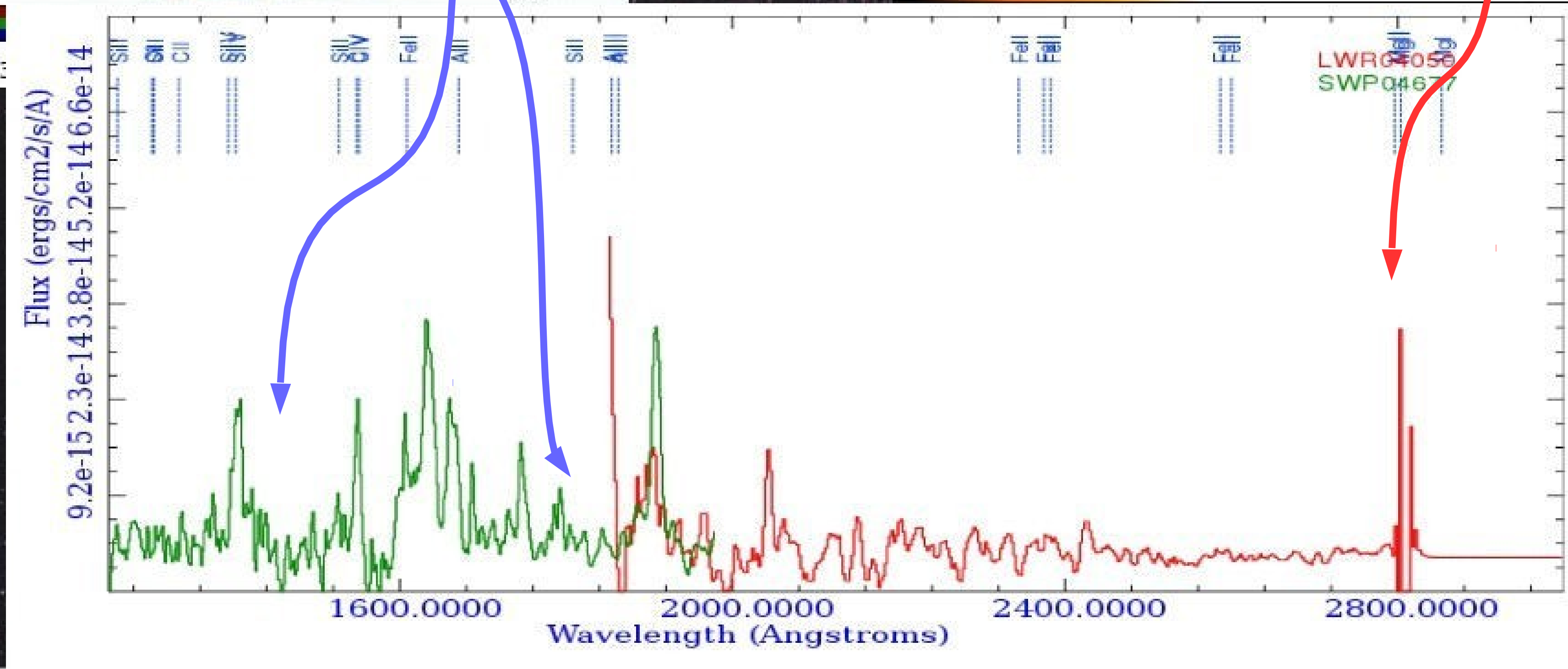
Spectral morphology of NGC 6960 – IUE & UVIT

RGB image (FUV BaF2 + Sap + Si)

UVIT Images credits: Sutaria, Rahna, Murthy, Singh, Ray, Rao and Kumar.

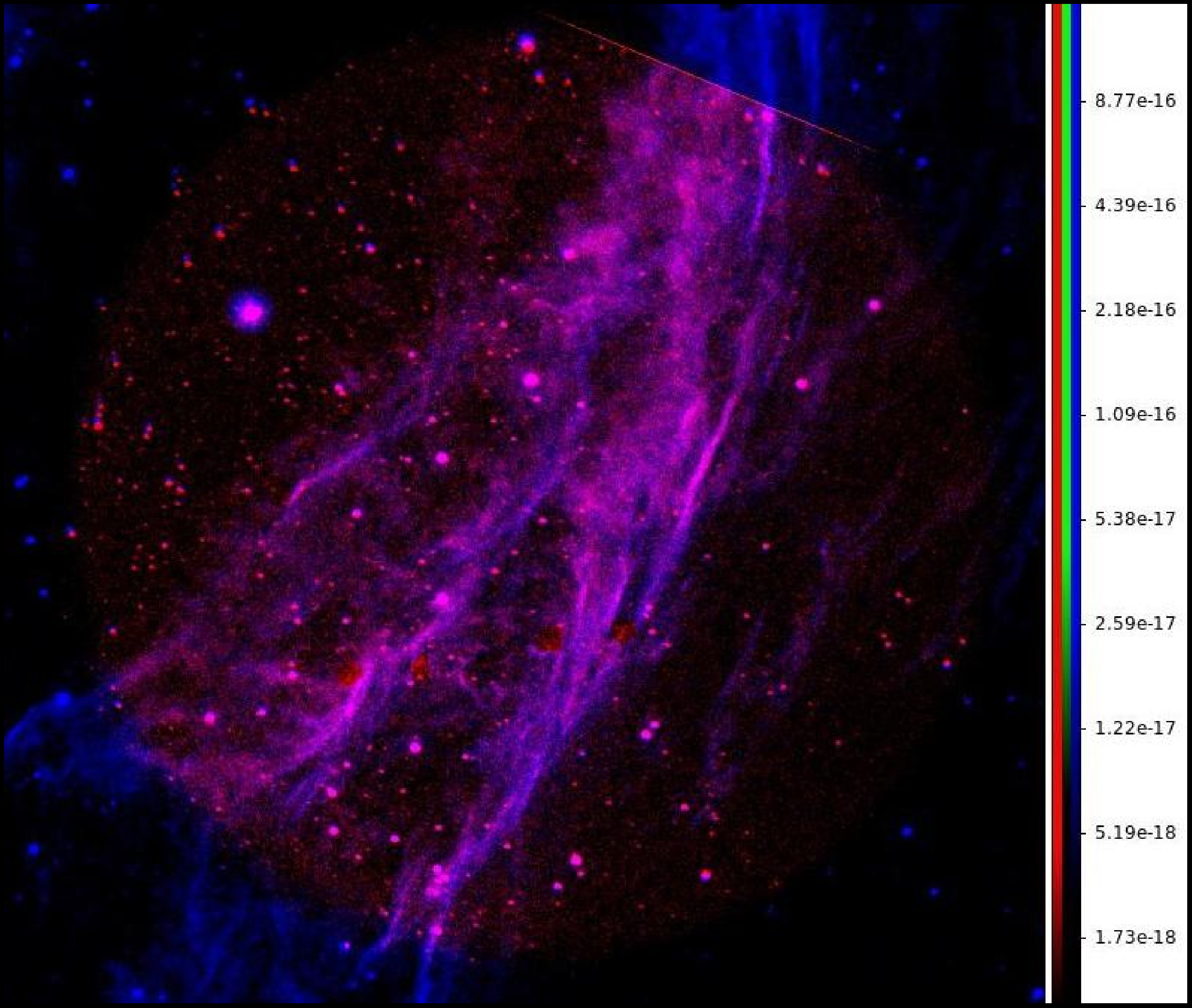
N279 image





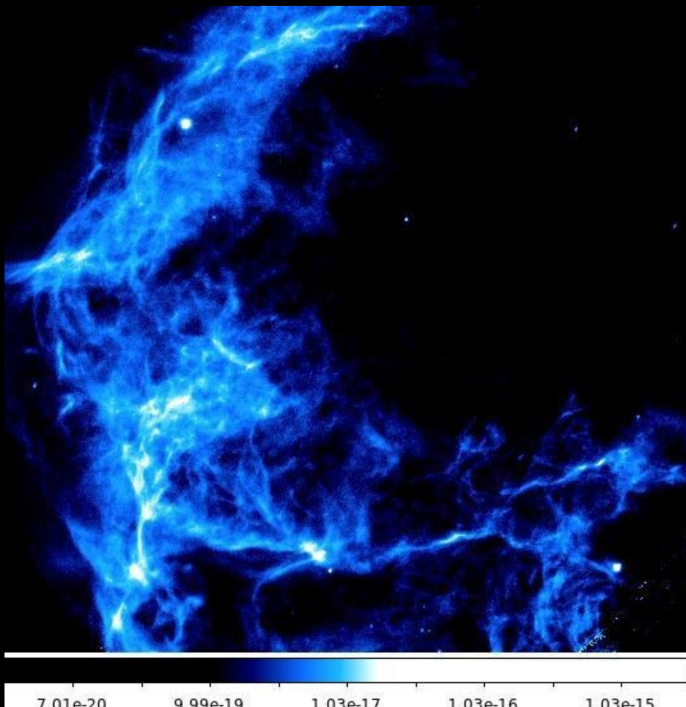
NGC 6960 across different epochs

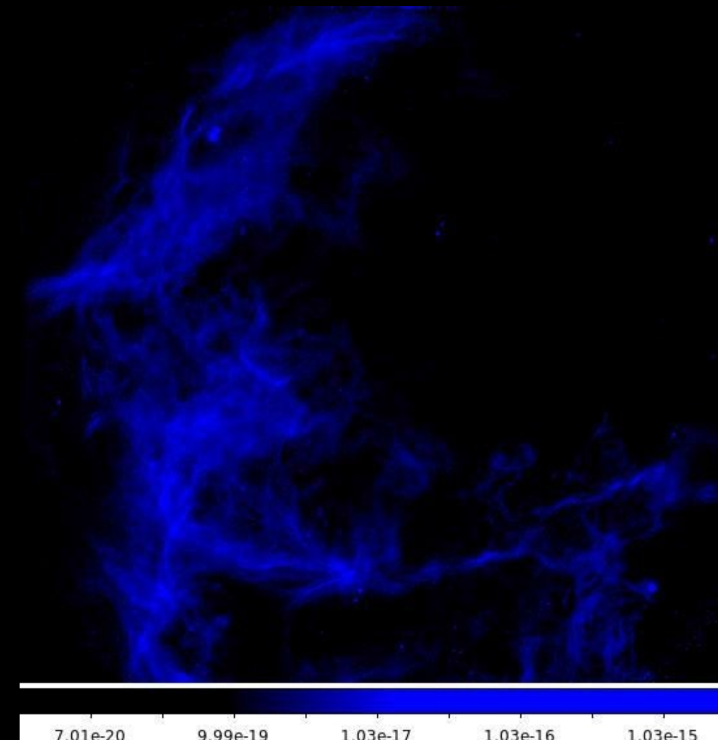
Flux calibrated B(Galex, 2011) and R (UVIT/N280, 2016) images superposed to show regions dominated by Mg II (2800 A) emission. ►



NGC 6995: The east wing of Cygnus

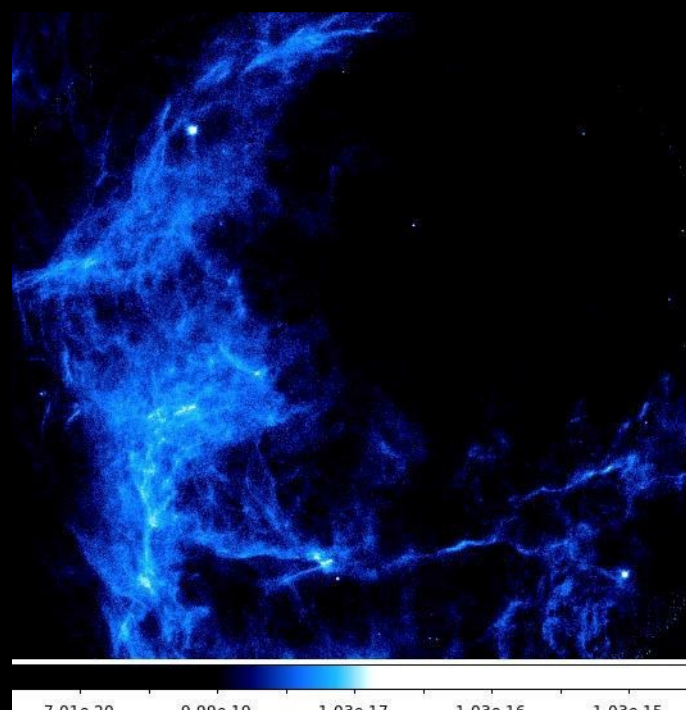
▼F154W (FUV-BaF2) image of NGC-6995.





▲F172M (FUV-Si) image of NGC6995.

UV excess in F154W -- BB tail of thermal X-ray emission, or line emission from Si IV (1396 A)? ▲►

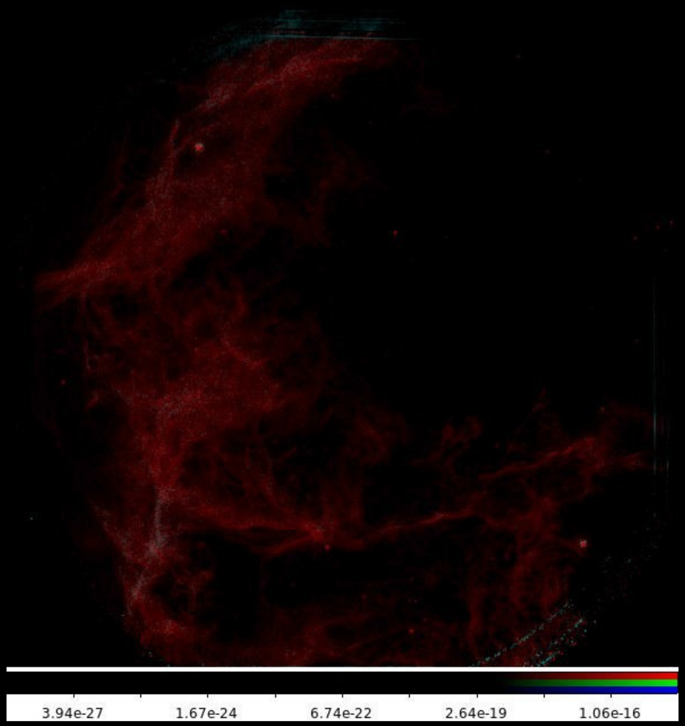


◄▲UV excess in F169M – dominated by C IV (1550 A) emission.

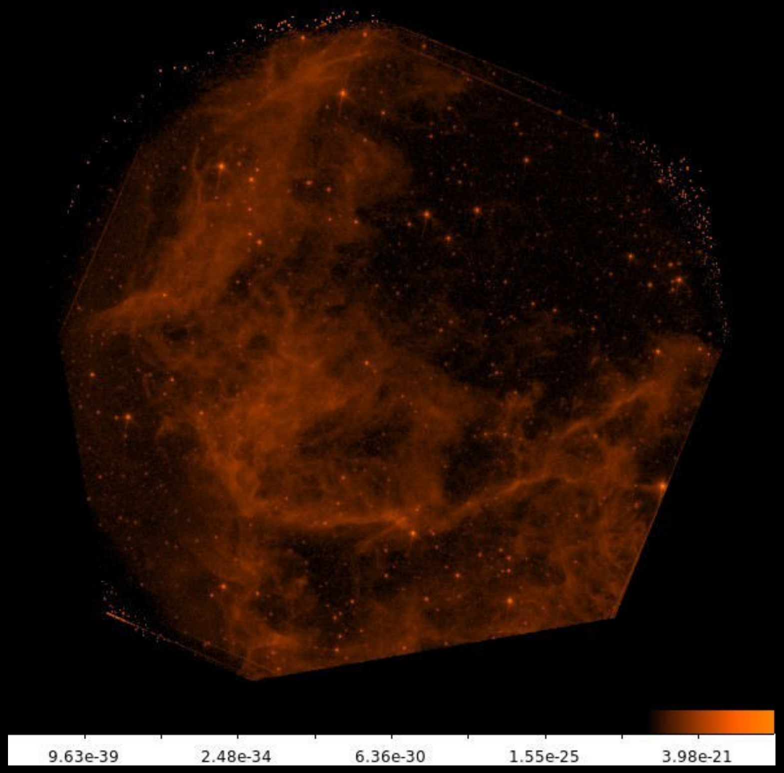
◄F169M (FUV-Sap) image of NGC6995.

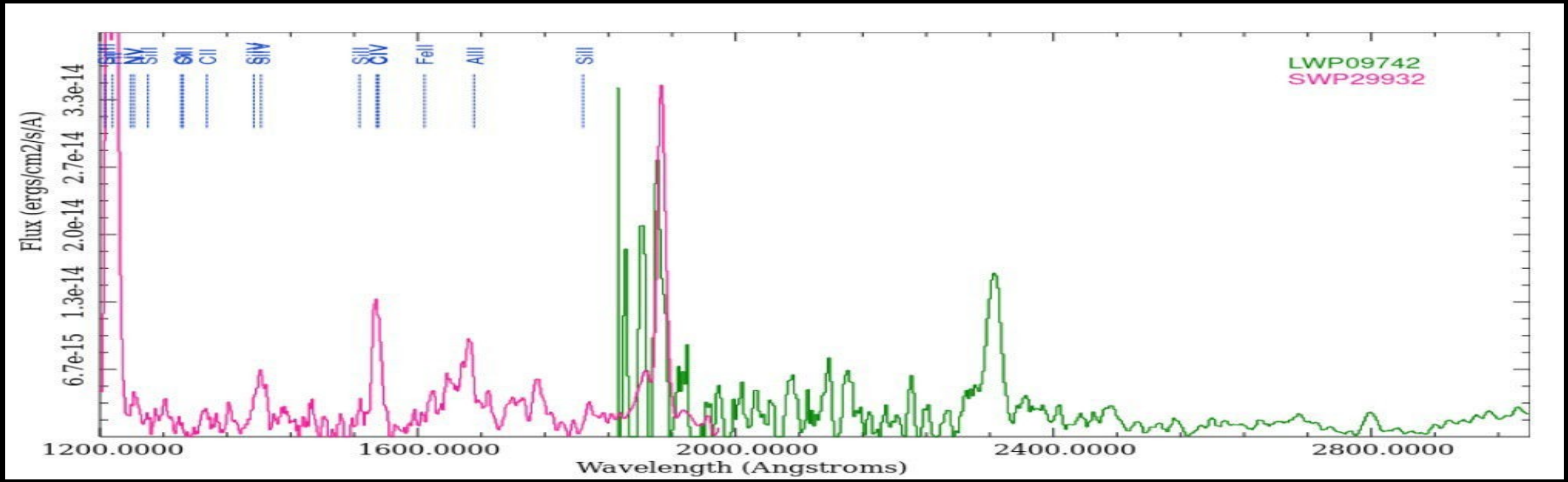
Spectral morphology of NGC 6995 – IUE & UVIT

R(1660 – 1780 A), G (1460-1660 A)
and B (1380-1660 A) composite of NGC6995.

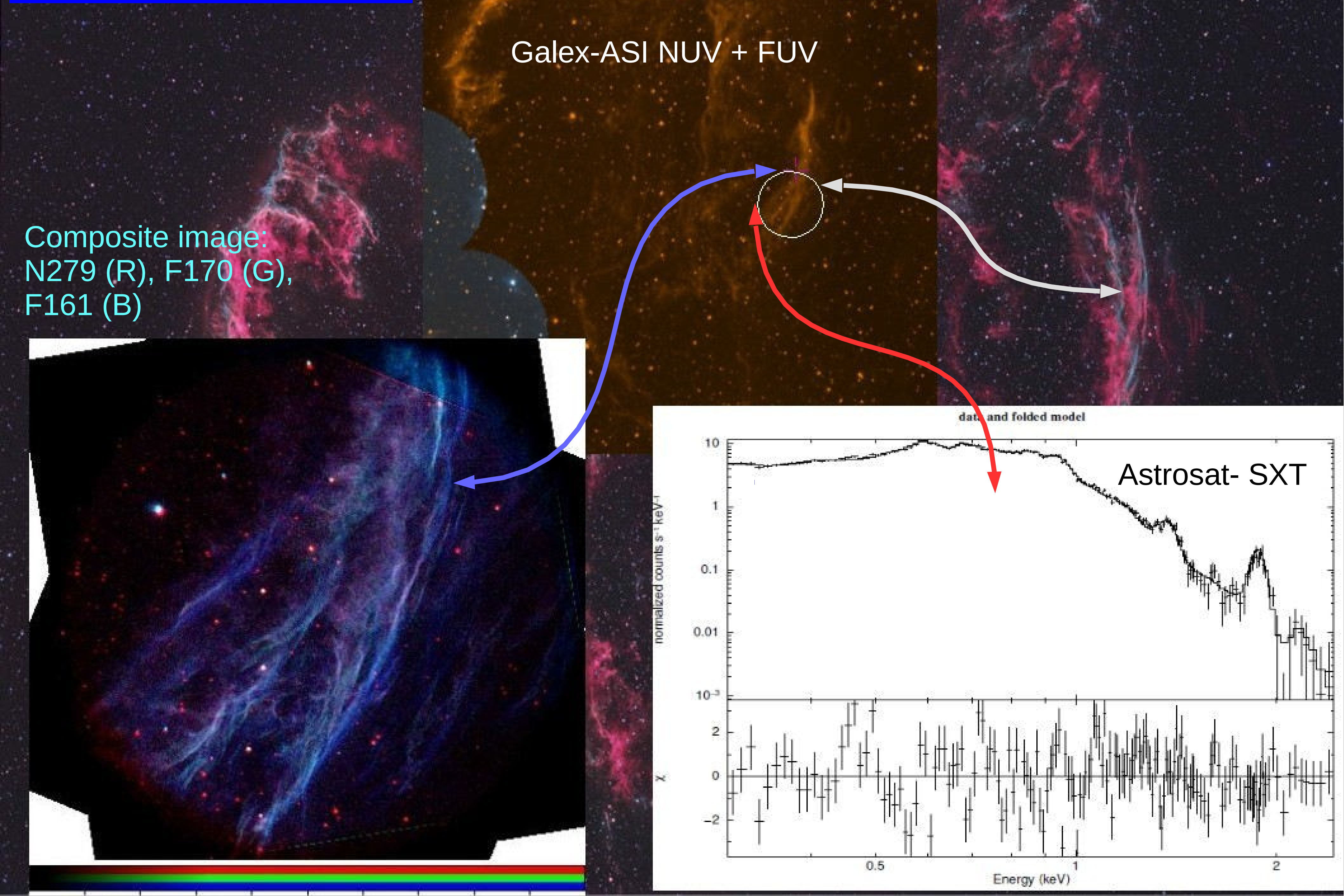


The same field in the (2750-2800 A) band.



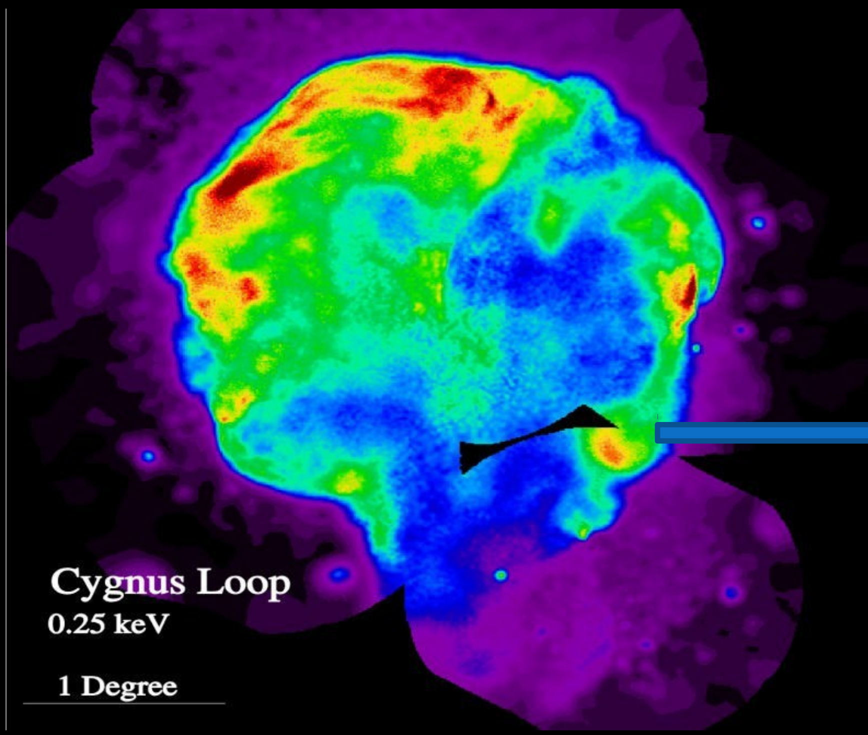


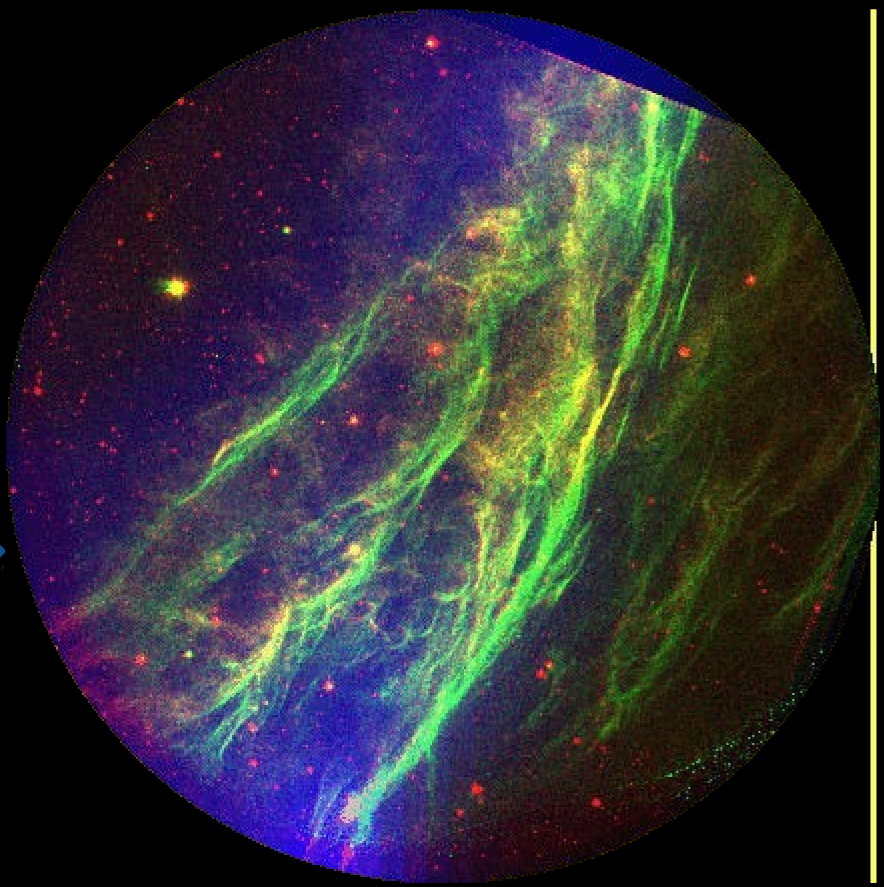
The many colors of NGC 6960



Spatial correlation between x-ray and UV emission

Confirms that most x-ray emission does occur from the Limb brightened shell





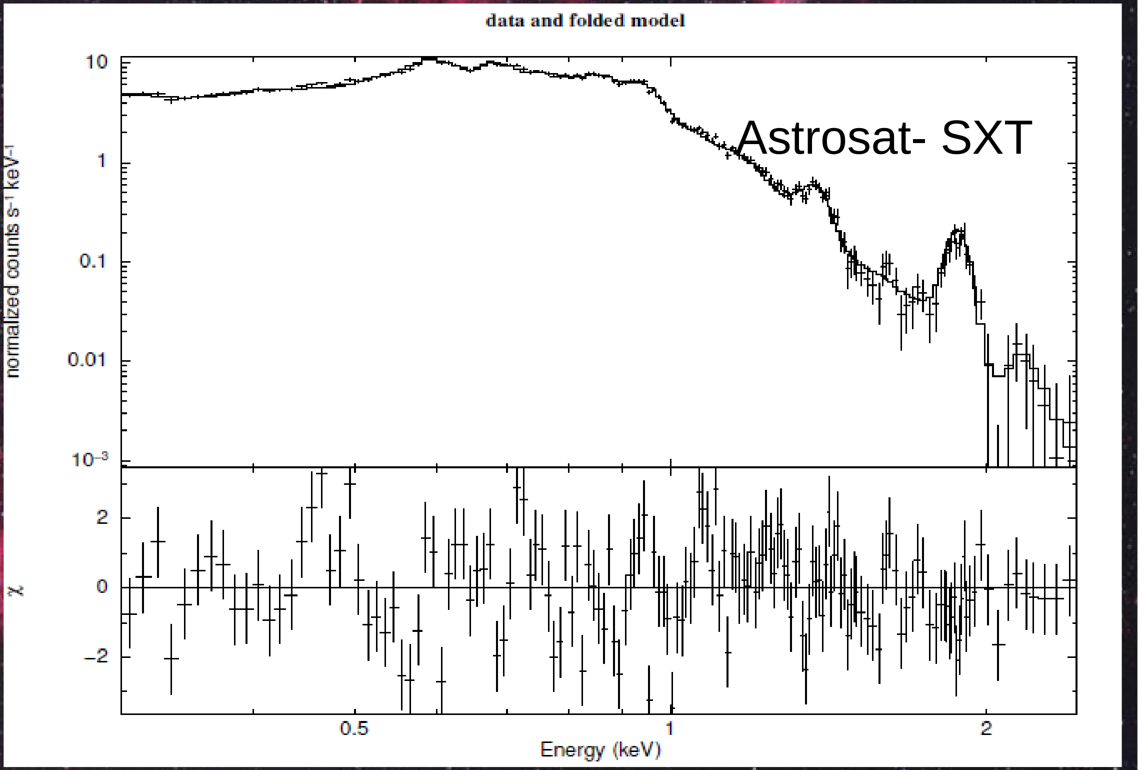
RGB Composite with N279 (R), F155 (G) and 0.1-0.3 keV (B)

NGC 6960 in Soft X-ray (SXT band)

Two thermal component X-ray plasma model with variable abundances, with T_1= 0.194 ± 0.002 keV and T_2=0.75 ± 0.01 keV.

Mg dominates in the low temp component,

High temp should be dominated by C and He.



Spectrum credit: K. P. Singh, Sutaria et al.

Other Results and Conclusions:

Flux: While NGC 6990 (Western Veil) emits dominantly in N279, F170 and F160, with little emission in F155, this Is reversed in the Eastern Veil, which Is brighter in F155 than in F170!

Property of molecular cloud which the Shock has run into, or an asymmetric Explosion? Or both?

Shock velocities from IUE between 100-200 km/s.
Comparison with Galex show NUV continuum as well as line emission.

Filters	Flux (erg cm^{-2} Å^{-1}s^{-1})	Normalized wrt NUVN2
BaF2	7.36794E-12	5.320
Sapphire	6.99997E-12	5.055
Silica	6.43248E-12	4.645
NUVN2	1.38480E-12	1.000