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CENTER for IMAGING SCIENCE
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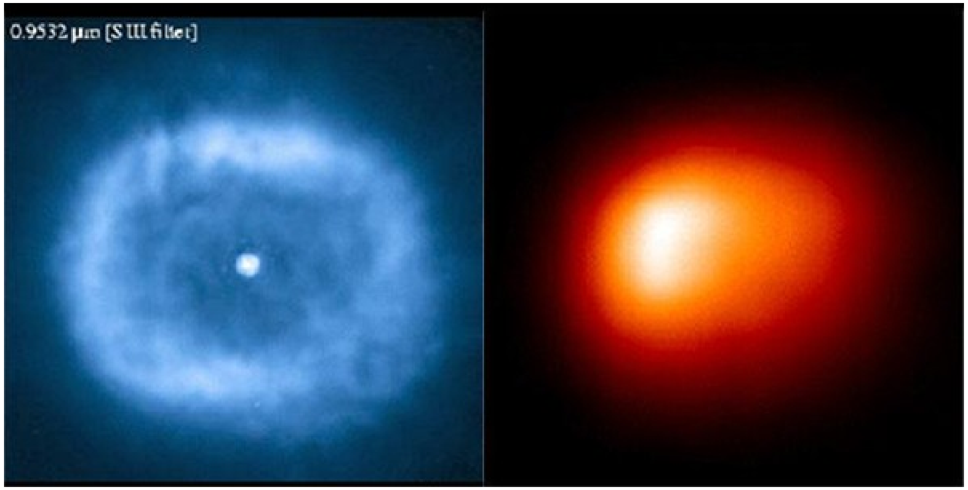
# X-Ray Emission from Planetary Nebulae: A Decade of Insight from Chandra





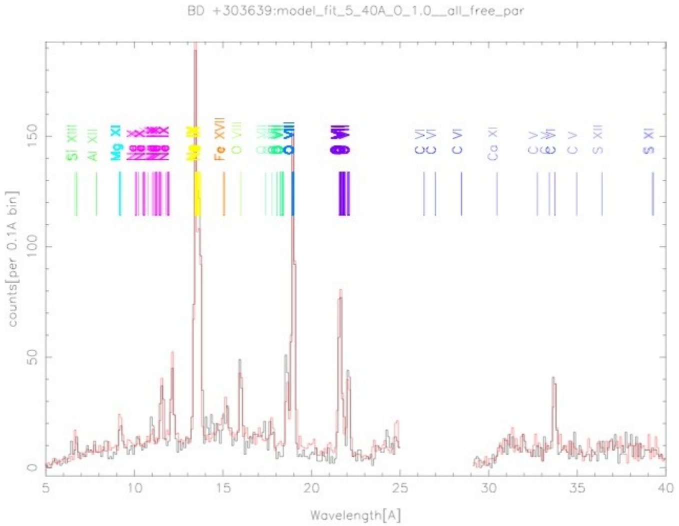
*Joel Kastner*

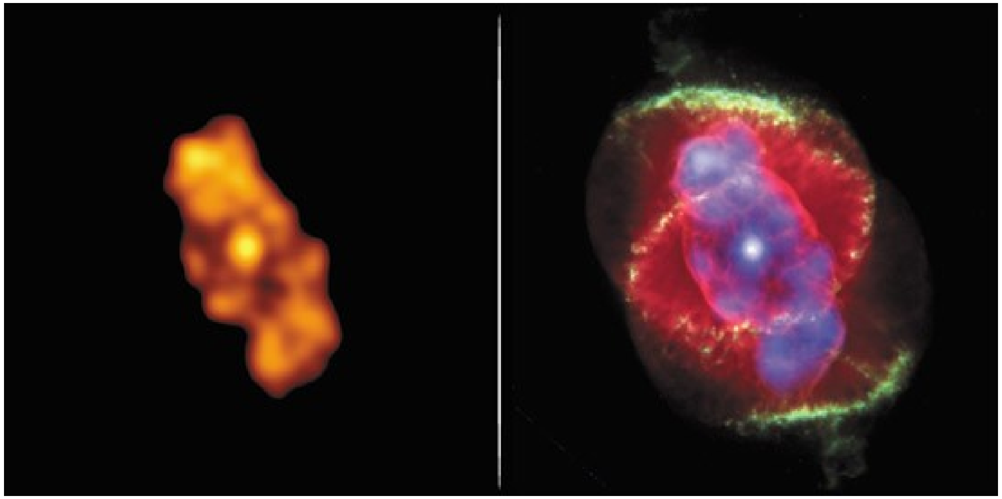
*Center for Imaging Science*

*and*

*Astrophysical Sciences & Technology*

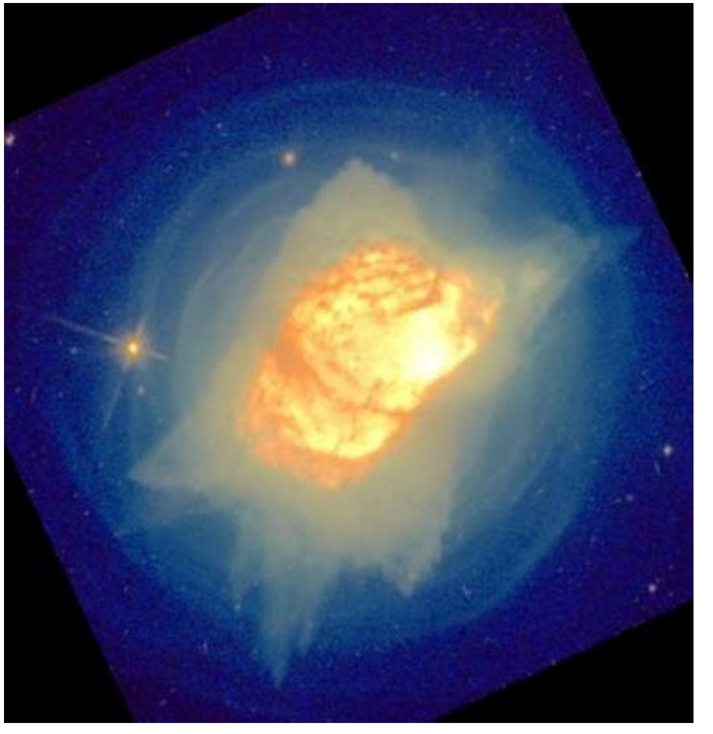
*Rochester Institute of Technology*

# Planetary Nebulae

- Near-endpoints of stellar evolution for 1-8 $M_{sun}$ stars
- PN: ejected red giant (AGB) envelope ionized by newly unveiled stellar core (emerging white dwarf)
- Dazzling variety of shapes
  - Shaping process(es) are presently subject of intense interest in PN community



*NGC 7027:*
*planetary nebula poster child*

# Planetary Nebulae: Favorite subjects for HST

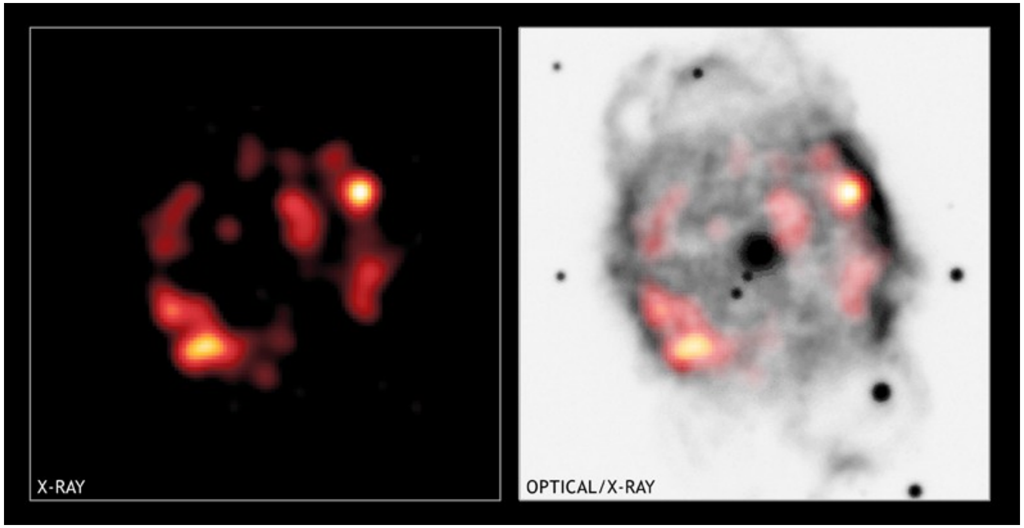
*HST/WFPC2 "last light": K 4-55*

*HST/WFC3 "first light": NGC 6302*

# X-rays and the Structure of PNs: A Decade of Insight

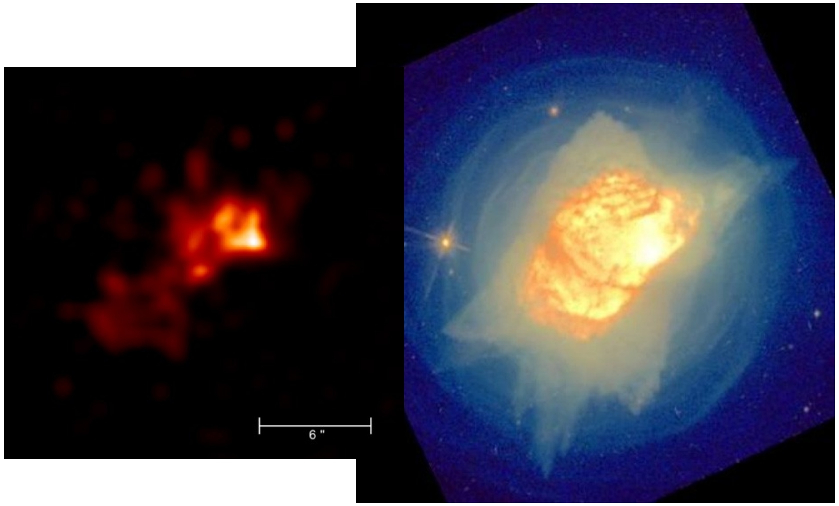
- Two classes of source detected in Chandra (& XMM) CCD X-ray imaging spectroscopy observations
  - Diffuse X-ray sources
    - Morphology traces wind interaction regions
      - “Hot bubbles” vs. collimated outflows
    - Abundance patterns should point to the source of the shocked (X-ray-emitting) gas
      - Present “fast wind” from PN core, AGB “slow wind”, or both?
  2. Central X-ray point sources w/ $kT_X$ ~ 1 keV (or more)
    - Not the photosphere of the newly exposed white dwarf…so origin uncertain

# Diffuse X-ray regions within PNe: "hot bubbles" and collimated outflows



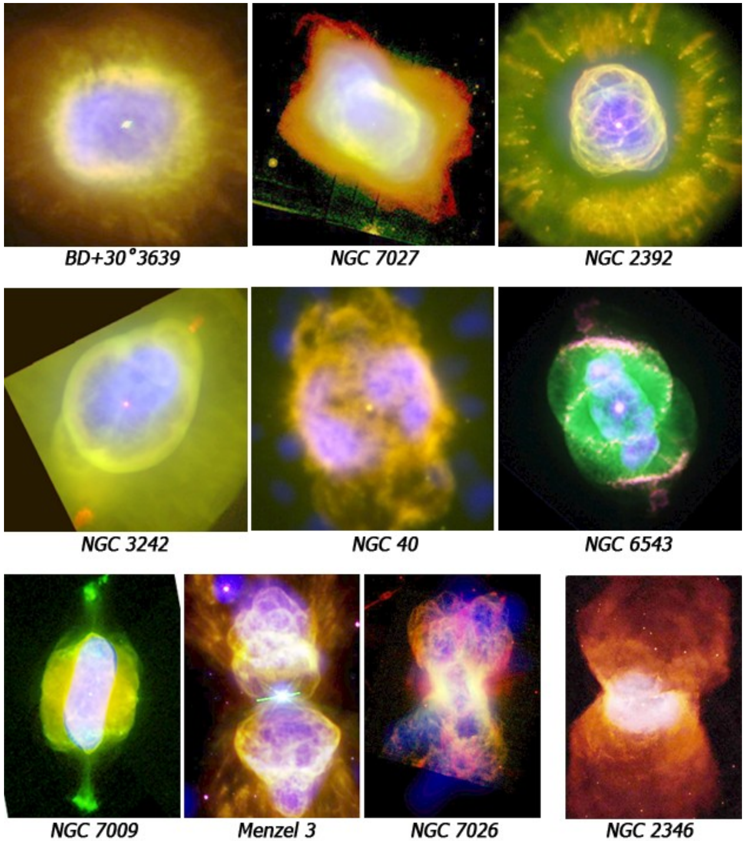

NGC 40: a hot bubble
*left: Chandra X-ray*
*right: X-ray superimposed on optical (WIYN) image*
*(Montez et al. 2005)*

NGC 7027: fast, collimated flows
*left: Chandra X-ray*
*right: HST*
*(Kastner et al. 2001)*



# Chandra & XMM-Newton: New light on "hot bubbles" in PNe

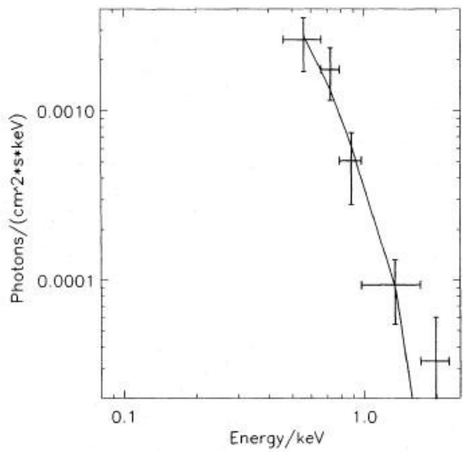
- Common traits of diffuse X-ray PN:
  - "Closed" bubble morphologies
    - Confinement of superheated plasma
  - Central stars have large wind kinetic energies
    - Most are [WC], [WO], or WR(H) types
      - X-ray luminosity correlated w/ wind luminosity



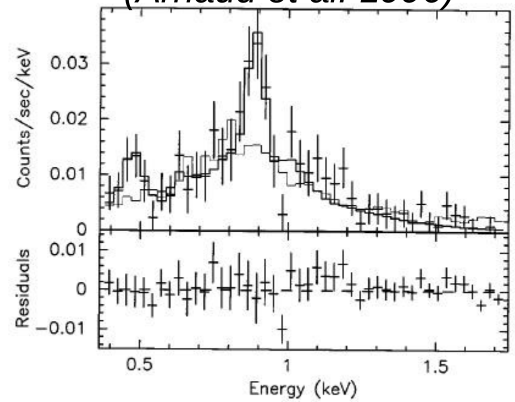

*X-ray images (blue): XMM & Chandra*
*X-ray/visual image overlays: M. Guerrero*
*Montage: B. Balick*
*(NGC 2346 is an X-ray NONdetection)*

# BD +30°3639: First and best target for PN X-ray spectroscopic studies

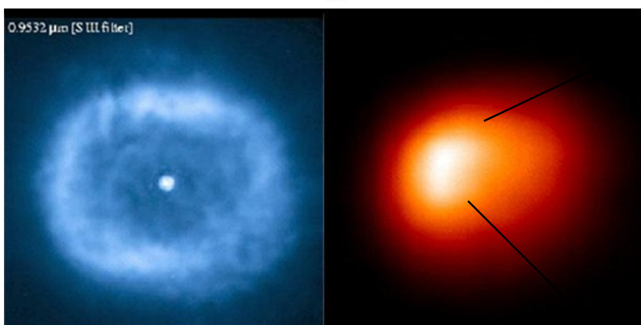
*ROSAT PSPC…*
*(Kreysing et al. 1992)*



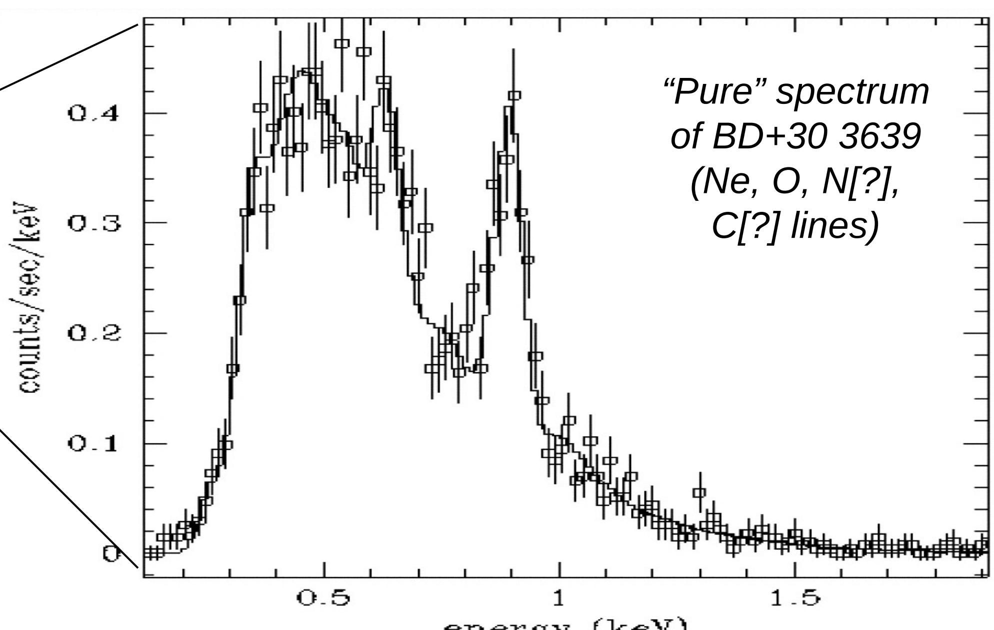

*…ASCA CCD (SIS)…*
*(Arnaud et al. 1996)*




*melange of BD+30 3639 (Ne, O lines) + background supernova remnant (continuum)*

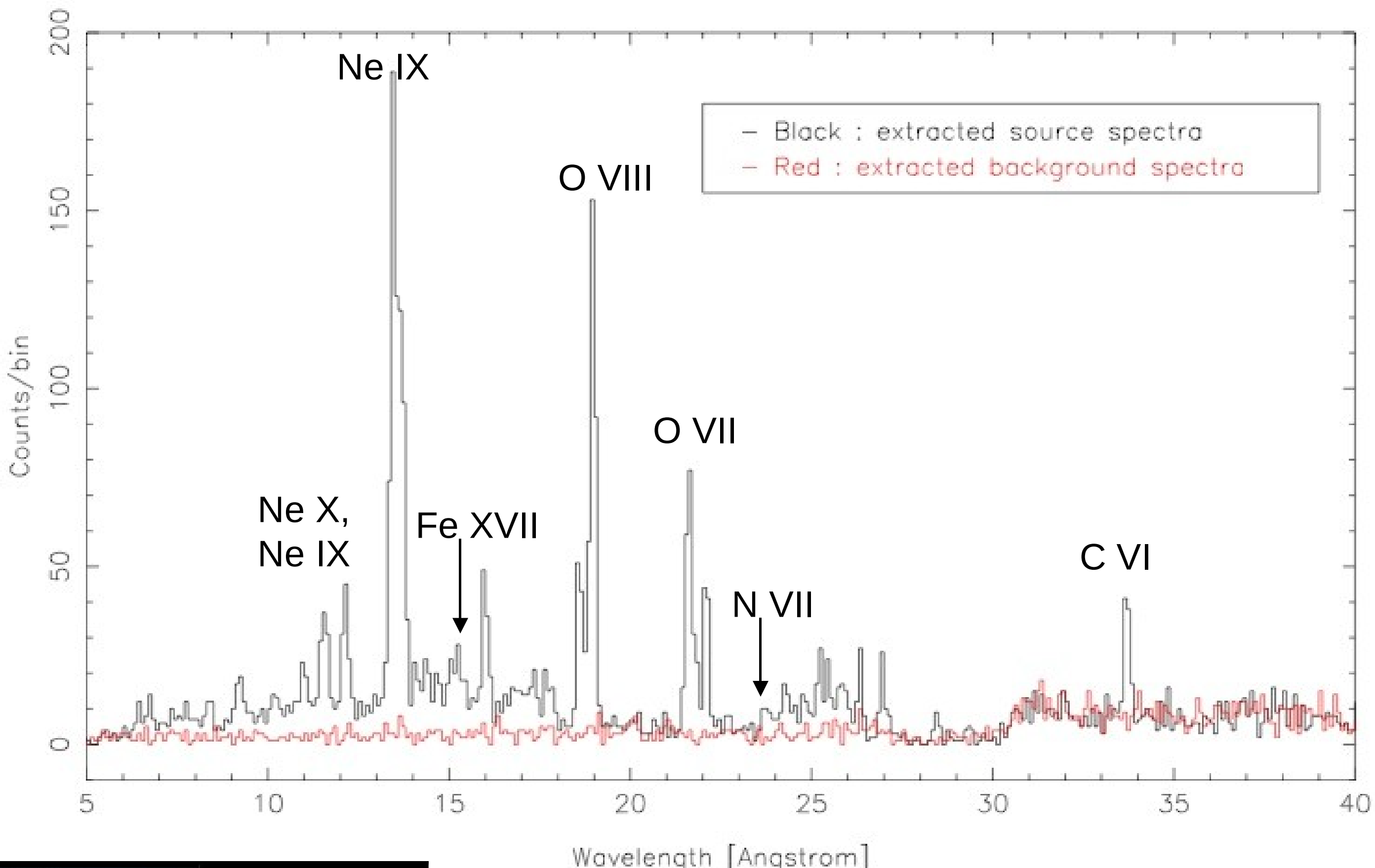



*…Chandra CCD (ACIS-S3)*
*(Kastner et al. 2000)*



# The one & only X-ray gratings spectrum of a PN to date: BD +303639

*300(!) ks w/ LETG/ACIS*




Two temperature components:

$T_1 = 2.9 \times 10^6$ K

$T_2 = 1.7 \times 10^6$ K

(necessary to fit both H-like & He-like Ne & O line ratios)

Abundances:

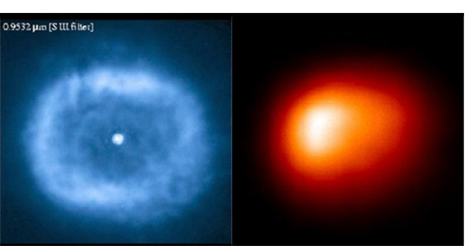
Ne/O = 3.3…5.0

C/O = 15…45

Fe/O = 0.1….0.4

N/O = 0.1…1.0

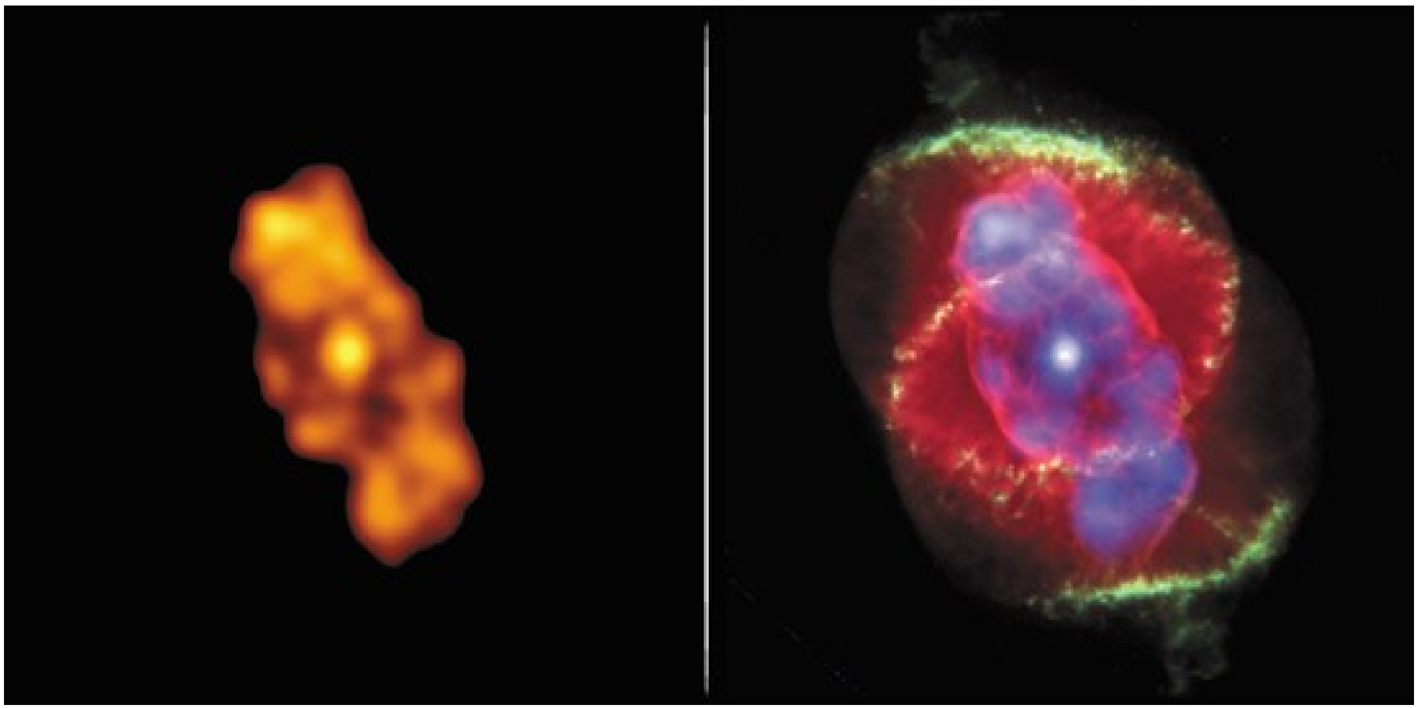
(90% confidence intervals)



*(Yu, Nordon, Kastner, et al. 2009; Nordon, Behar, et al. 2009)*

# X-ray point sources at PN cores: What is going on at the central star?

Point sources are detected in ~30%*
of PNe observed by Chandra

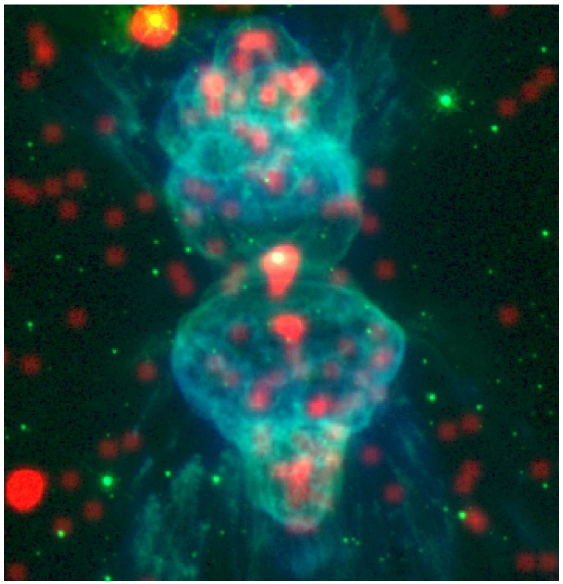


*Prime example: the Cat's Eye (NGC 6543)*
*(Chu et al. 2001)*

* not including "PNe" w/ symbiotic Mira central star binary systems

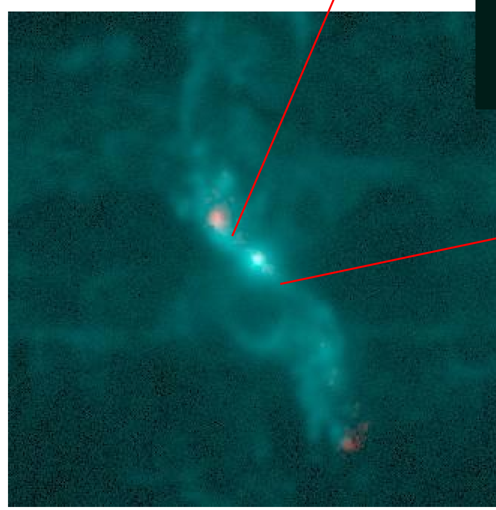
# Clue: central X-ray point sources are common (ubiquitous?) among symbiotic-Mira* “PNe”

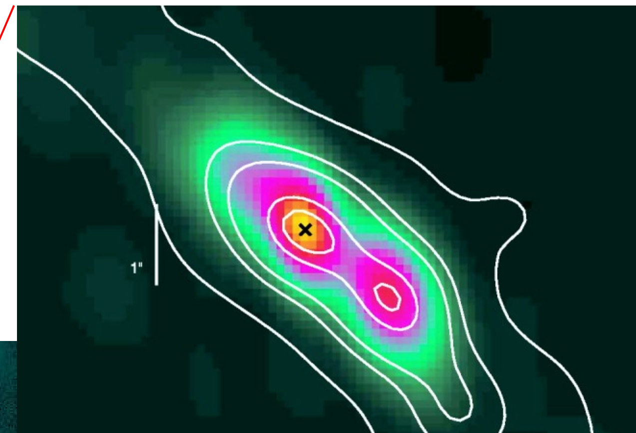
*Binary system: AGB star & white dwarf w/ accretion disk (and jets?)



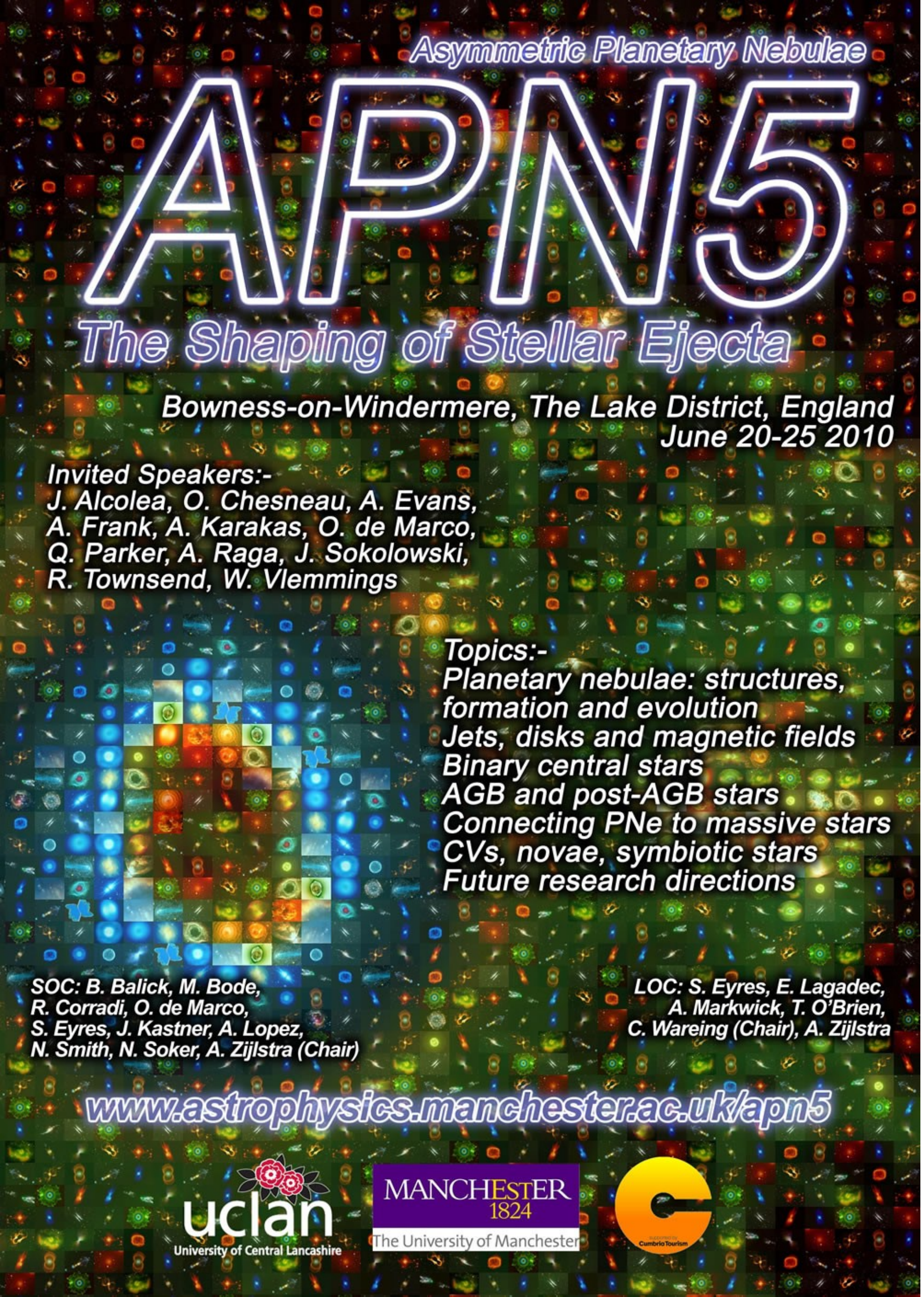
*Above: Menzel 3 (Chandra [red] & HST [blue]; Kastner et al. 2003)*

*Below: R Aqr (Chandra [red] & NOT [blue])*





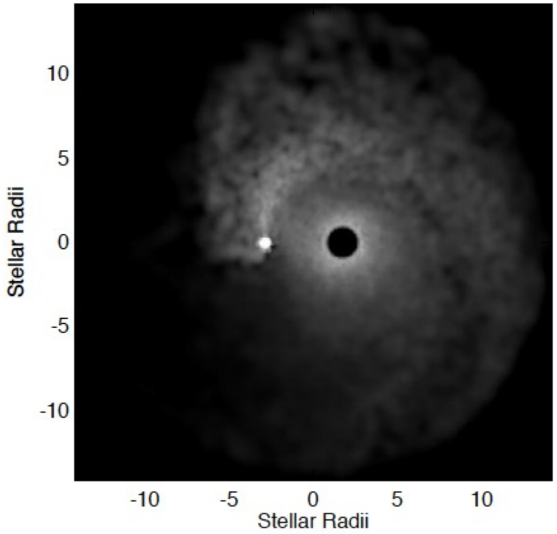
*Above: Chandra contours on VLA 3.5 cm image (Nichols et al. 2007)*




- “Understanding the intricate structures of planetary nebulae represents one of the most vexing problems in astrophysics.”
  - Similar structures are seen in a variety of circumstellar environments, including nova shells and massive star ejecta.
  - The primary suspects: binary companions and/or the effects of magnetic fields.

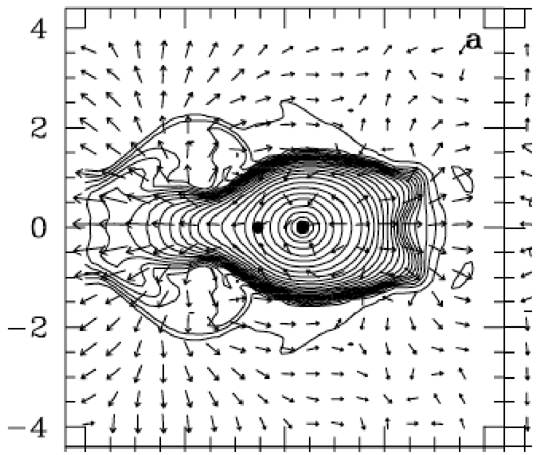
# Binarity and the shaping of planetary nebulae

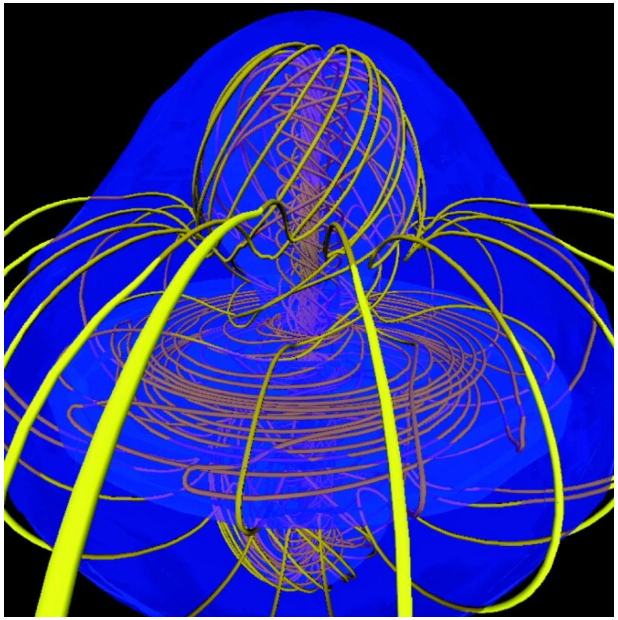
Motivation: 1980's papers by Livio, Soker, Morris




Above: disk formation via binary interactions at AGB star stage (*Mastrodemos & Morris 1999*)

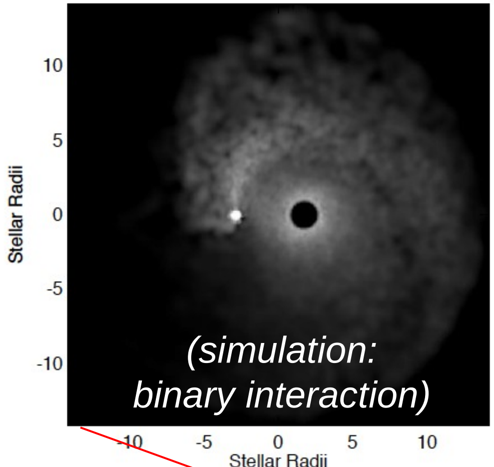
Below: rapid, collimated mass ejection due to a common envelope phase (*Sandquist et al. 1998*)

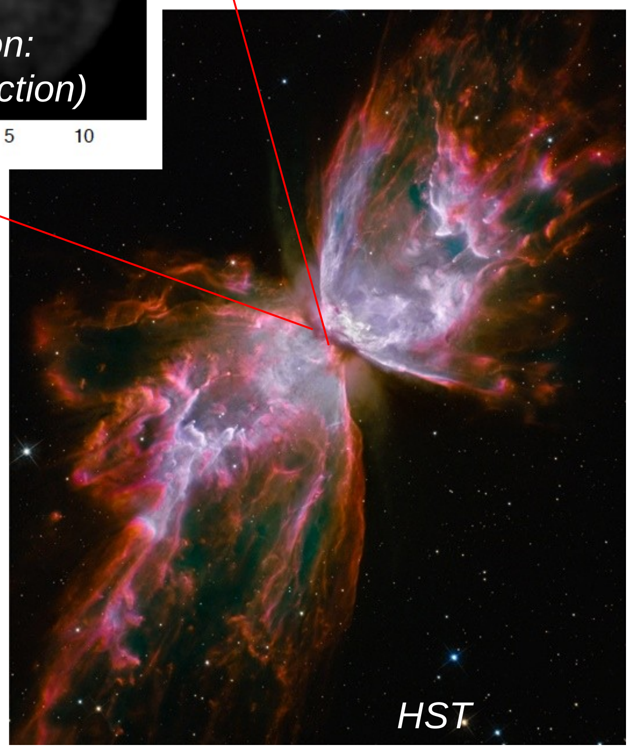


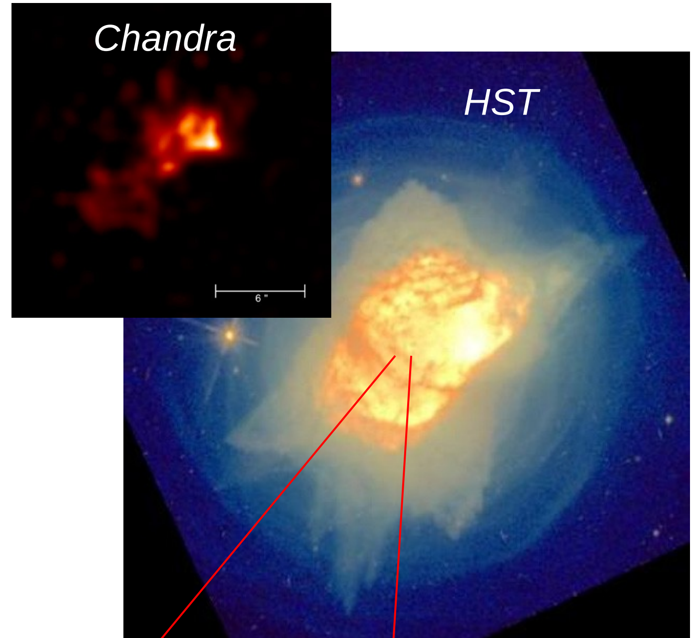
Above: rapid, collimated mass ejection via a magnetized, rotating envelope (*Matt, Frank, & Blackman 2006; Nordhaus, Blackman & Frank 2007*)

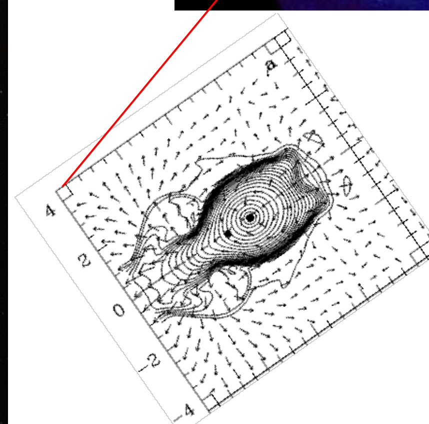
# Binarity and the shaping of planetary nebulae




NGC 6302: disk formation via binary interactions at AGB star stage? (*above: Mastrodemos & Morris 1999*)



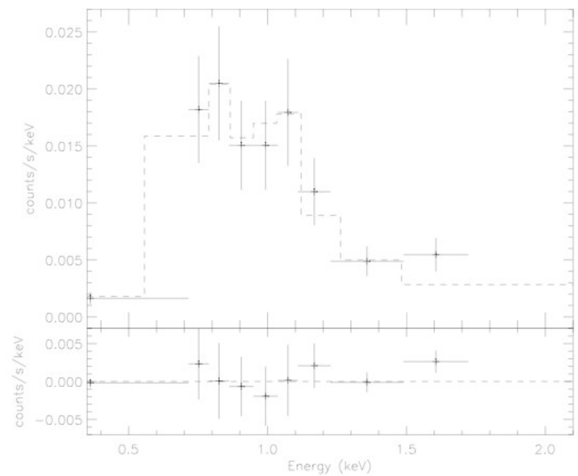




NGC 7027: rapid, collimated mass ejection due to a common envelope phase? (*left: Sandquist et al. 1998*)

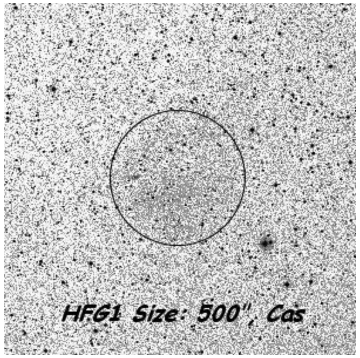
# Pilot study of PNe w/ binary central stars: preliminary results

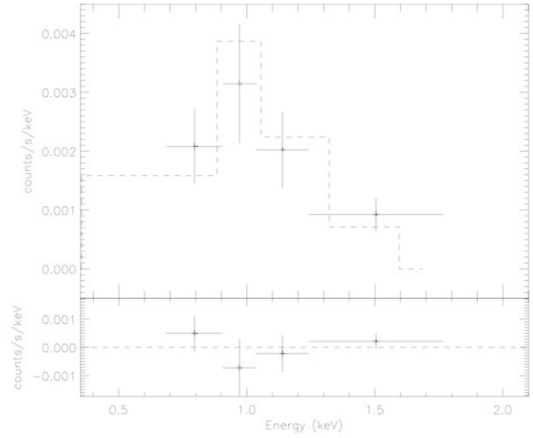
*Montez, De Marco, Kastner, Chu, & Soker (2010, in prep.)*

- Motivation: low-mass companions to PN progenitors (mass-losing AGB stars) should be spun-up and (hence) X-ray-luminous
  - Jeffries & Stevens 1996; Guerrero et al. 2001; Soker & Kastner 2002
- Two program PNe are known binary systems w/ late-type MS companions
- Results: X-ray point sources detected at both PNe central stars
  - X-ray luminosities consistent w/ predictions based on companion spectral types (Soker & Kastner 2002)




PN HFG 1: F9 V
$L_X \sim 1.7\times10^{30}$ erg/s
$T_X \sim 1.8\times10^{7}$ K



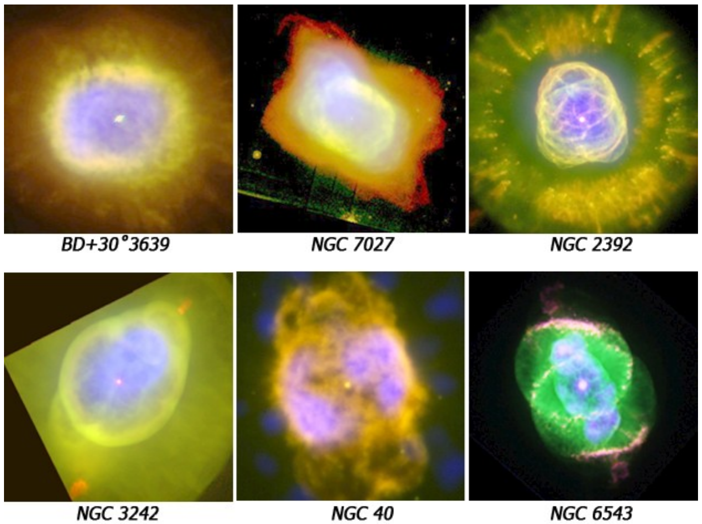



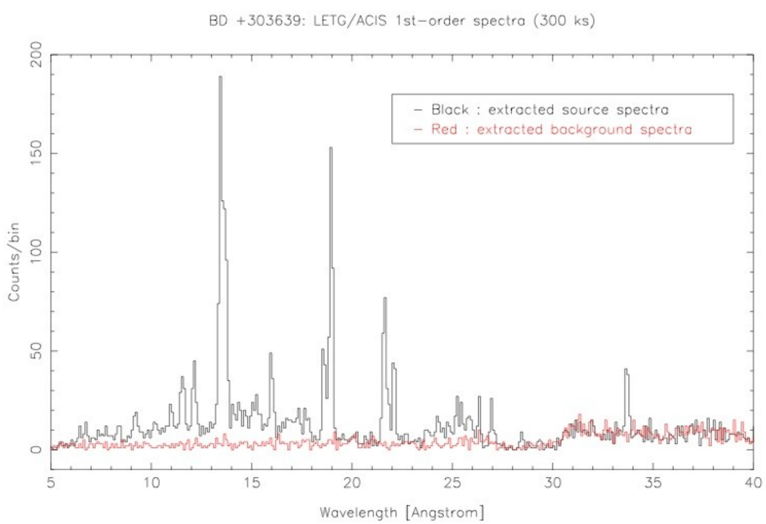

PN DS 1: M4 V
$L_X \sim 5.3\times10^{29}$ erg/s
$T_X \sim 1.2\times10^{7}$ K

# Summary: X-rays from Planetary Nebulae

- Imaging spectroscopy of diffuse emission within PNe has yielded unique insight into stellar wind collisions, shocks, and the late stages of stellar evolution
  - “Hot bubbles” vs. collimated outflows
  - Last, crucial phases of solar-mass stellar nucleosynthesis
- …but X-ray point sources within PNe may hold the key to understanding their shaping mechanisms
  - Relating binarity, magnetic fields, and disk/jet formation
  - Understanding PNe as just one more “wavelength window” within the overall spectrum of binary star behavior
    - CVs, symbiotic stars, LMXB, HMXB, …, GRBs?!

# X-rays from Planetary Nebulae: 10 years of Chandra insight, 10+ more to go…?



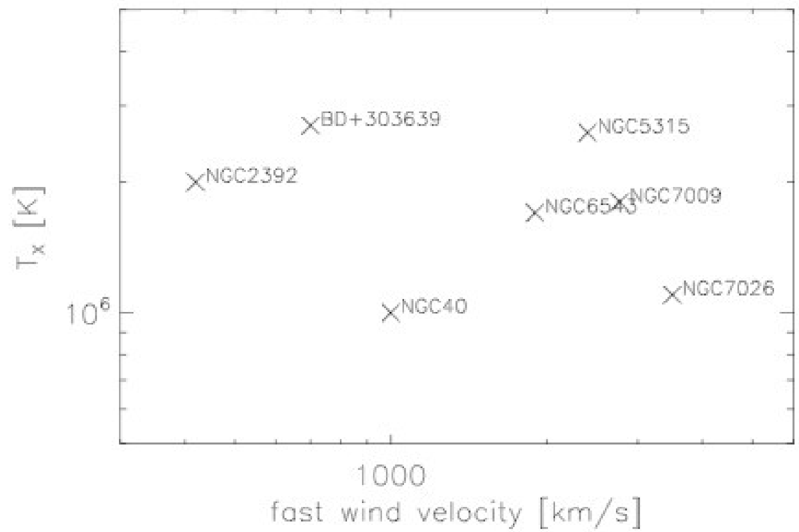



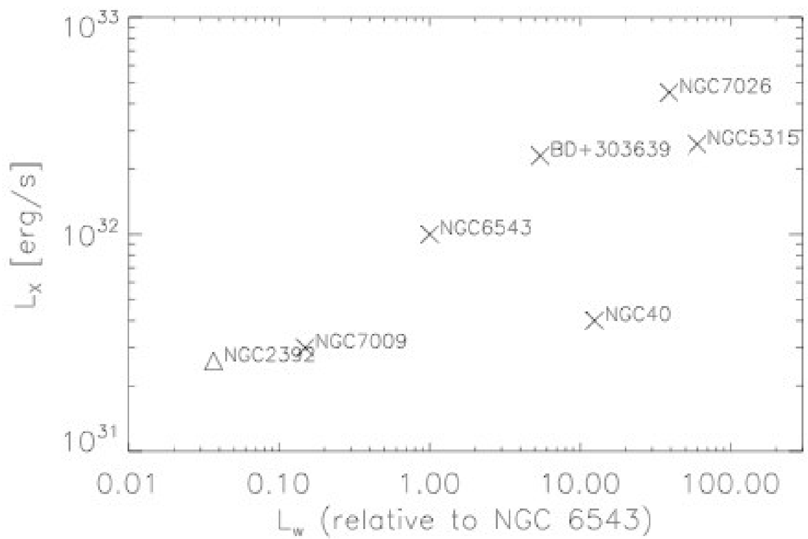

# “Understanding Planetary Nebulae: Strategic Research Collaborations” *Recommendations*

- “A coordinated, multiwavelength observational campaign targeting the *central stars* of planetary nebulae (CSPN) is necessary, if we are to make further progress in our understanding of the mechanisms that shape planetary nebulae.”
- Among the specific recommendations:
  - “A high-resolution X-ray imaging spectroscopic survey of very young PNe to search for accretion disks, jets, coronal activity, and wind shocks associated with CSPN and/or their companions.”

# Hot bubble X-ray sources: trends

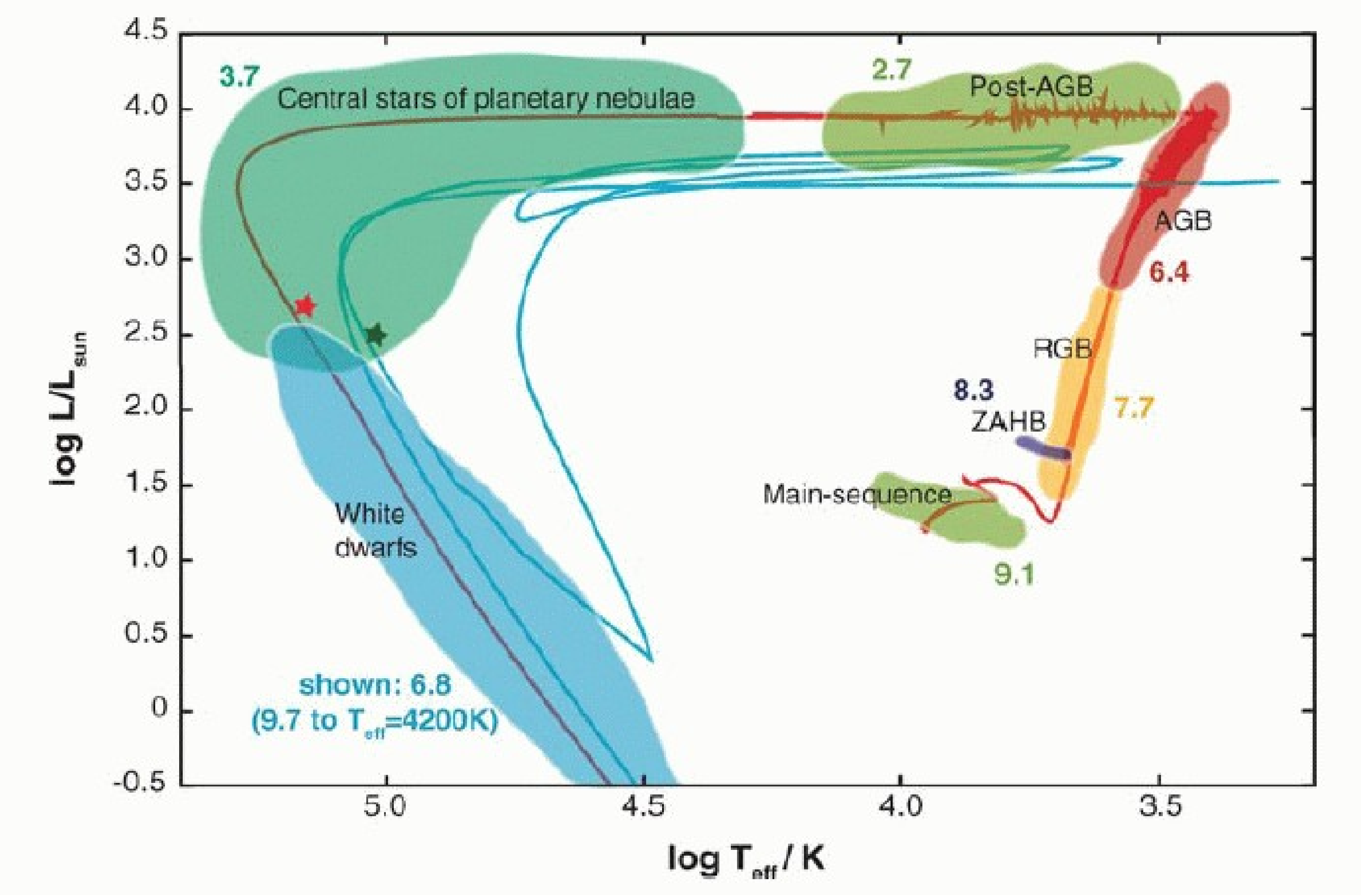
- X-ray temperature and present-day central star $V_w$ appear uncorrelated
  - Effects other than present-day shock strength determine $T_X$
    - Time evolution of $V_w$
    - Heat conduction from "hot bubble" plasma to $10^4$ K nebular plasma
    - Mixing of "hot bubble" plasma with $10^4$ K nebular plasma
    - Simple adiabatic cooling
- Weak correlation between $L_x$ and present-day stellar wind luminosity



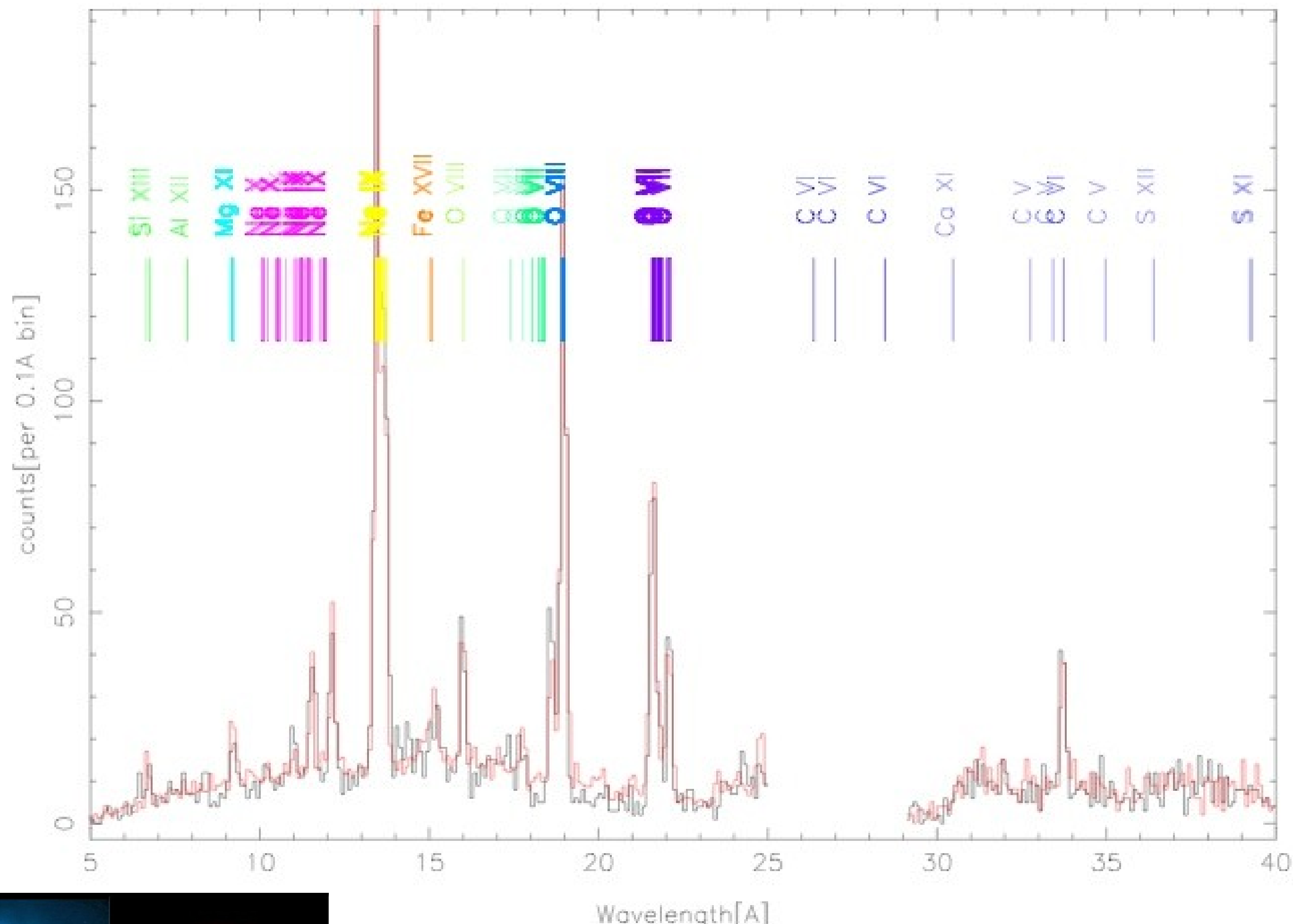

*Kastner, Montez, et al. (2008)*

# Evolution of a *single* 3 $M_{sun}$ star




*Herwig (2005, Ann. Rev. Astron. Astrophys.)*

# Best-fit model

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Abundances:
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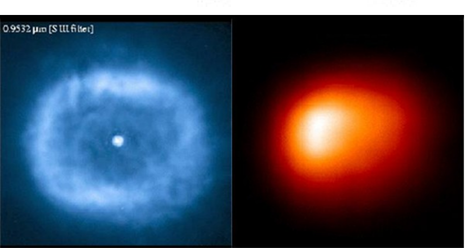
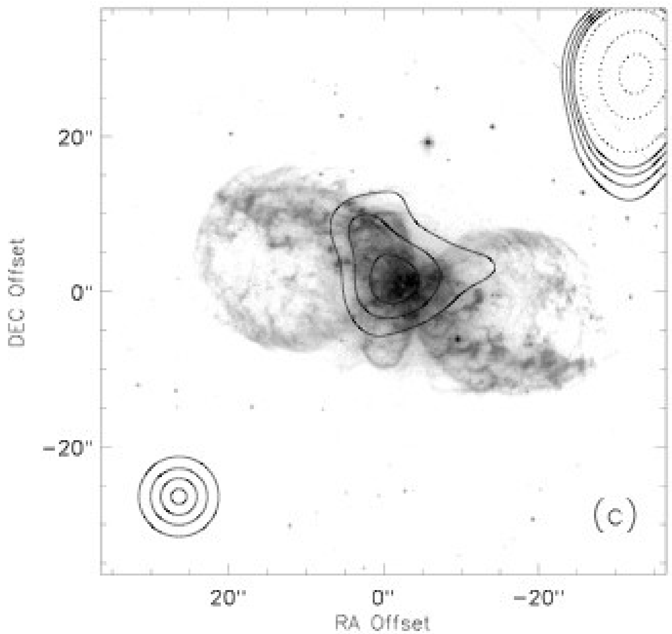


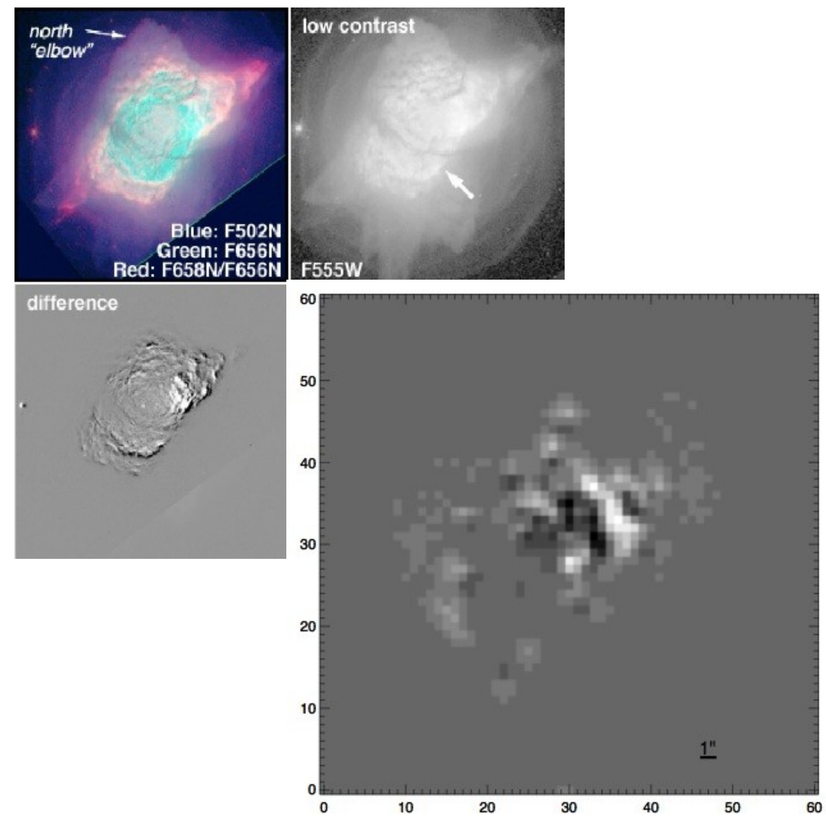
*Yu, Nordon, Kastner, et al. (2009)*

# Archival Studies




*Discovery of X-rays from Hubble 5 (XMM contours on HST image; Montez, Kastner, Balick, & Frank 2009, ApJ…*

*…first result of our NASA ADA program to analyze all serendipitous XMM observations of PNs)*




*EXAMPLE: actual HST measurement of proper motion in NGC 7027 (upper left 3 panels; Balick, pvt comm) and predicted X-ray proper motion over 10-yr baseline (lower right; Yu et al, Cycle 11 CXO proposal)*