X-Ray Imaging Spectroscopy of Planetary Nebulae in the Chandra/XMM Era: New Insight into Stellar Jets

*Joel Kastner**

Center for Imaging Science,
Rochester Institute of Technology
and
Laboratoire d'Astrophysique de Grenoble

* with help from lots of other people, and in particular:
Rudy Montez & Young Sam Yu (RIT Imaging Science Ph.D. students)

Planetary Nebulae…in the Context of Protostellar Jets

- In the case of YSOs and pre-MS stars:
  - Circumstellar disks are a natural consequence of (indeed drive) the very process of star formation
  - Jets are intimately tied to accretion processes
- BUT in the case of planetary nebulae:
  - Evidence (and theoretical motivation) for disks and jets is still controversial*
  - Outflow collimation (even precession) evident; however…
    - disks don't *have* to be present
    - Binarity *likely* plays central role (…Jovian planets…?)
    - Magnetic fields *may* play important role

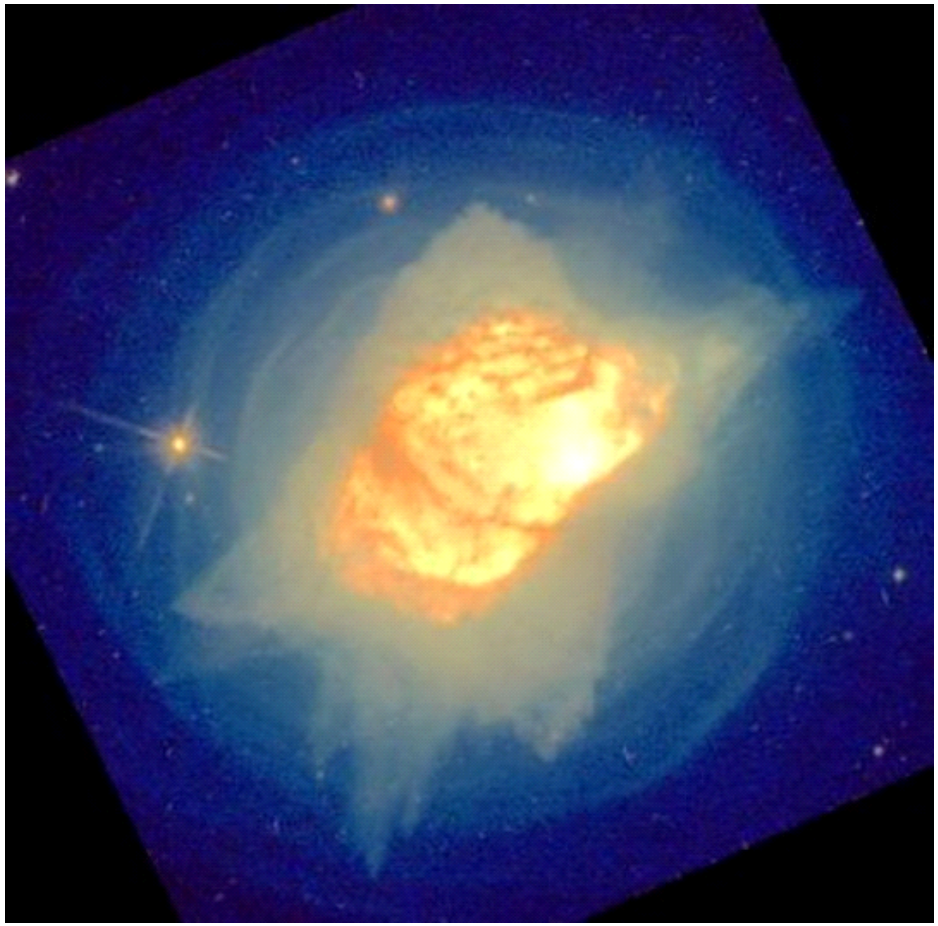
*primary motivation for ongoing *Asymmetrical Planetary Nebulae* conference series (see also posters by M. Akashi & A. Riera, this conference)

So why isn't this debate settled by now?

Main reasons:

a) In optical/IR, core regions of "key" young PNe are highly obscured by gas & dust
   - Case in point: NGC 7027 (right: HST)

b) Young PNe have highly luminous central star(s)
   - ~10^4 L_{sun} core easily outshines binary companions & makes disk/accretion/B-field signatures hard to detect

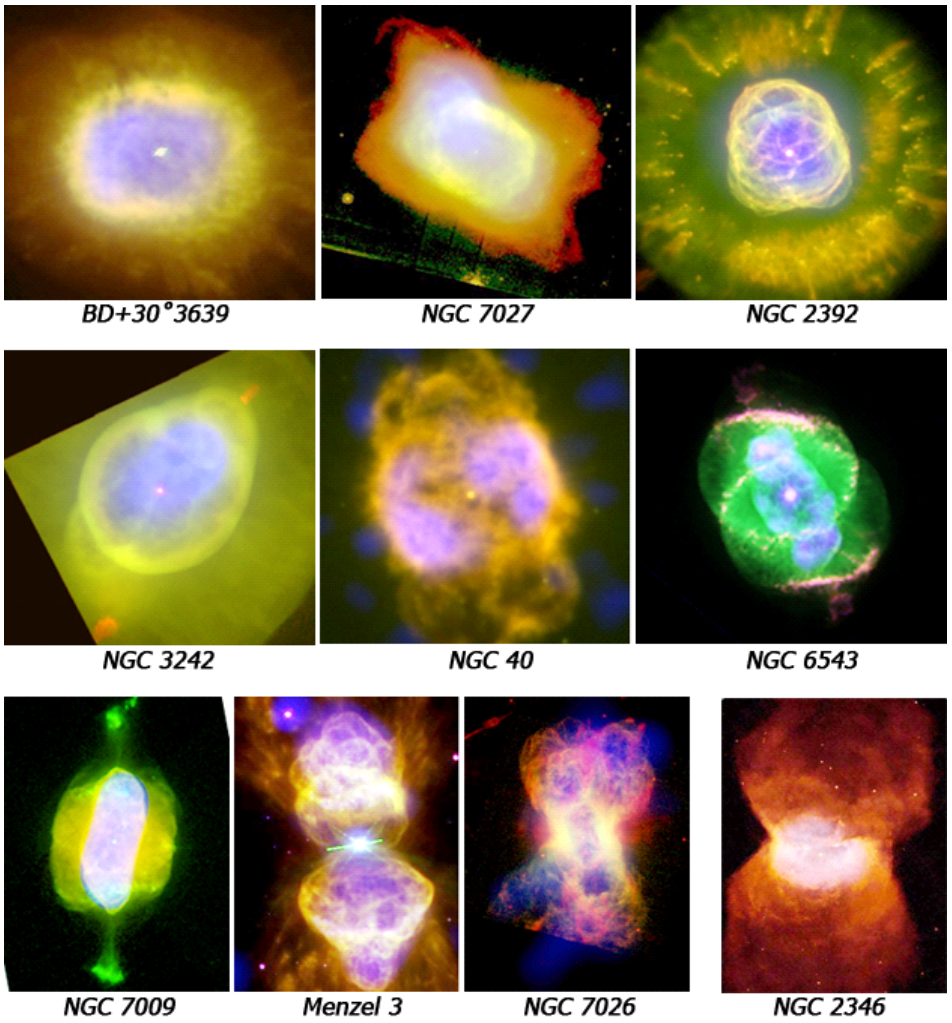


Why look to X-ray observations for help?

1) "Interacting winds" models for formation/shaping of PNs predict formation of X-ray-emitting *"hot bubble"*
   - Bubble blown by "new", fast (300-2000 km/s) stellar wind from PN core should lie within slow (10-30 km/s), photoionized ejecta of cool (AGB star) progenitor
   - Action of overpressured hot bubble on surrounding "cool" ionized gas could, on its own, produce characteristic PN shapes (spherical, elliptical, bipolar)?
2) Probe of star-disk interactions at PN cores
   - X-rays might reveal the binary companions and accretion disks that are possible agents of outflow collimation
3) Perhaps even detect the elusive jets themselves…?
   - Case in point: the closely related systems R Aqr and CH Cyg (as per invited talk by J. Sokoloski)

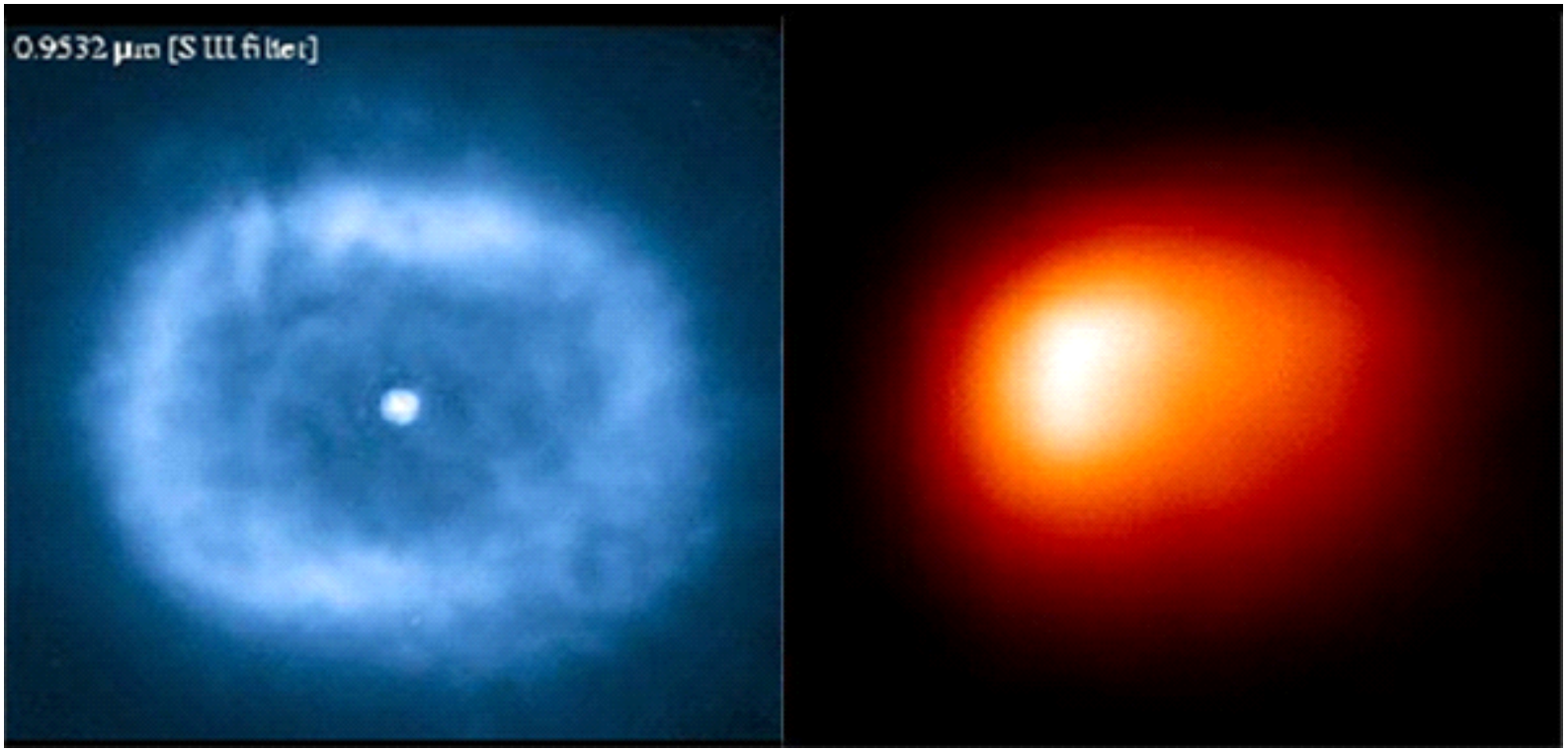
1) Hot bubbles within PNs

- Since 2000, Chandra and XMM-Newton have provided compelling X-ray evidence for “hot bubbles” due to PN wind interactions
  - About 35% of (~25) planetaries observed appear as diffuse X-ray sources
  - When detected:
    - Central stars drive particularly energetic present-day winds
    - X-ray emission is (usually) confined to cavities within closed optical bubbles
  - But there are caveats!
    - T_x is too low and is independent of V_{wind}
    - see Kastner et al. (2008) & refs therein



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

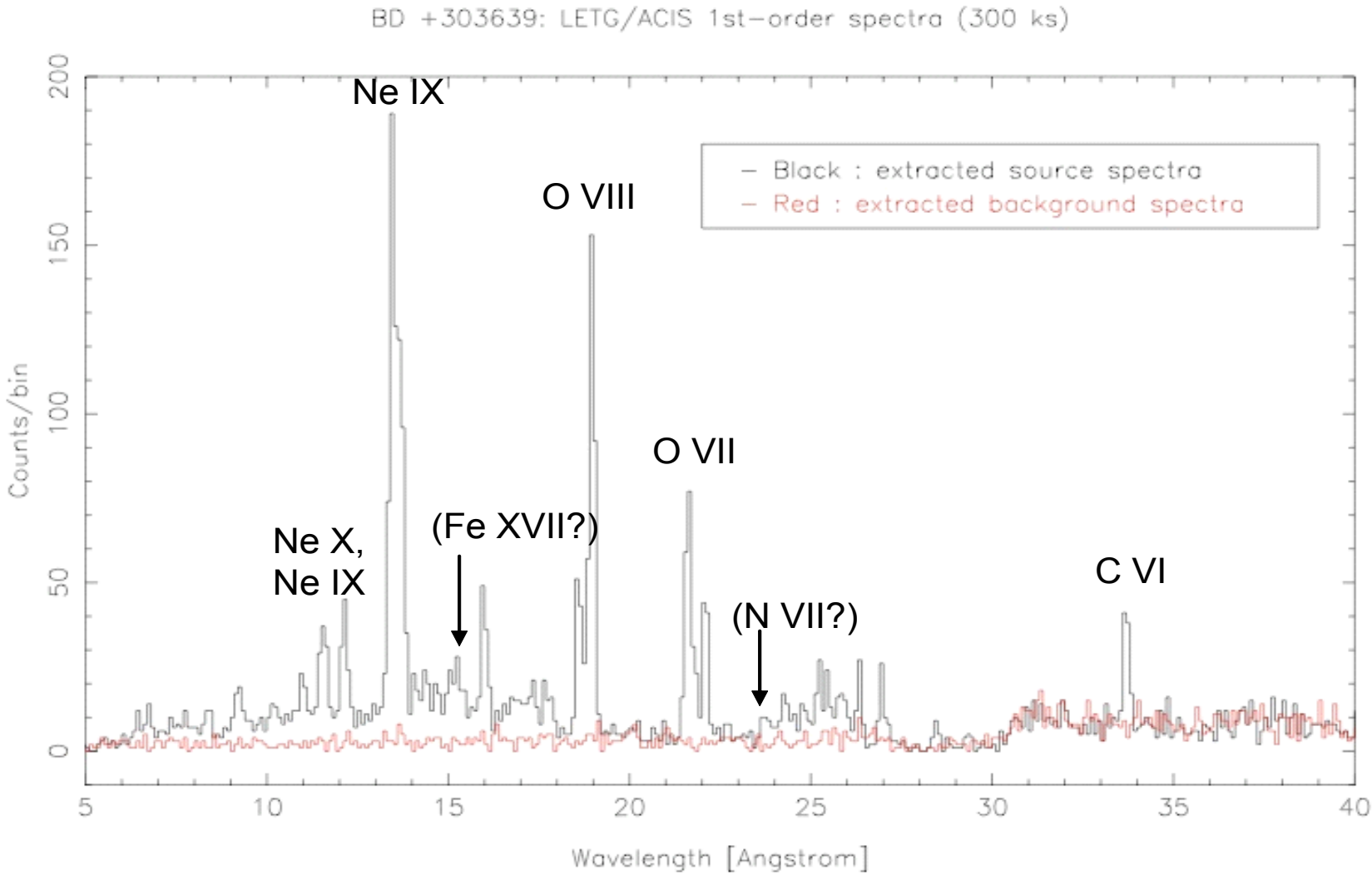
BD +30 3639:
The Prototypical* “Hot Bubble”



Left: HST [SIII] image
Right: Chandra Cycle 1 X-ray image (0.3-2.0 keV)
(Kastner et al. 2000)

**Caution, this object also displays molecular “bullets” (Bachiller et al. 2000)*

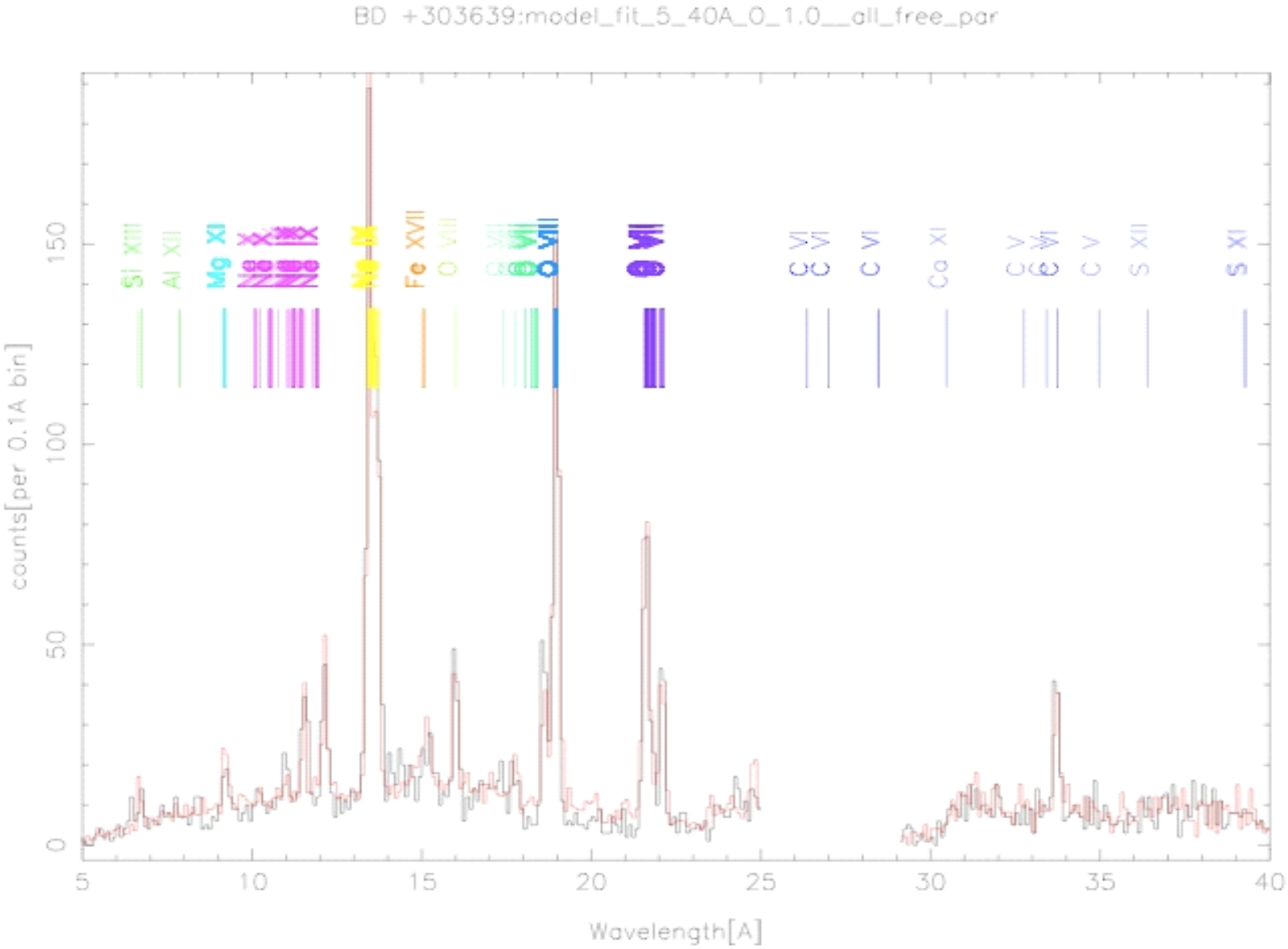
The Chandra LETG/ACIS spectrum of BD +30 3639



300 ks of Chandra exposure time!

(Yu, Nordon, Kastner et al. 2008, ApJ, submitted)

Best-fit model: a shocked [WC] star wind



N_H = 2.3e21 cm^{-2}

Two temperature components:
$T_{x,1}$ = 3.0x10^6 K
$T_{x,2}$ = 1.8x10^6 K
(necessary to fit both H-like & He-like Ne & O line ratios)

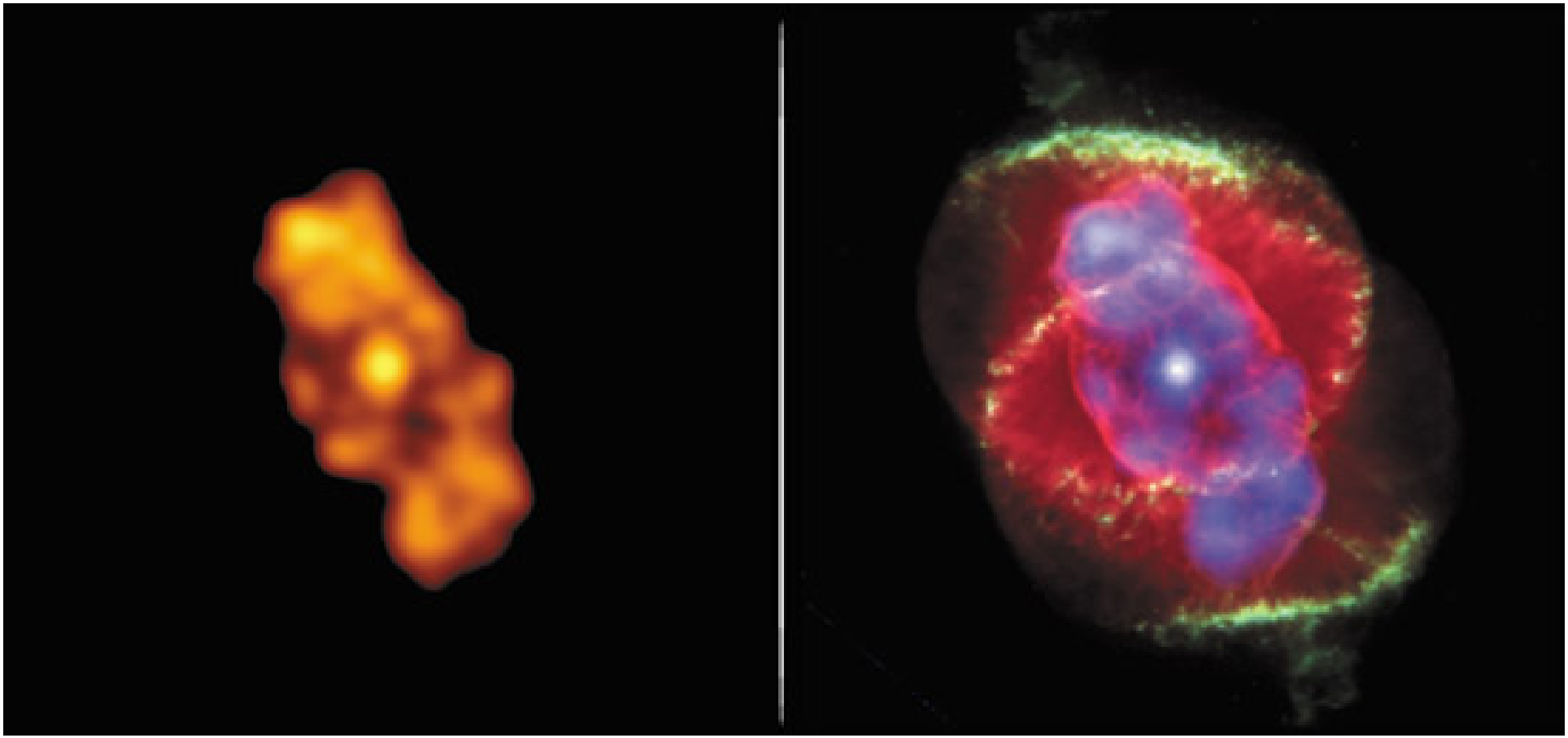
Abundances:
Ne/O = 3…5
C/O = 15…45
Fe/O = 0.1….0.3
N/O = 0.0…1.0
(90% confidence intervals)

Yu, Nordon, Kastner et al. (2008, ApJ, submitted)

2) X-rays from PN cores: constraints on outflow collimation mechanisms

- We have been systematically revisiting all Chandra observations of PNe to place constraints on point source X-ray luminosities (Montez & Kastner, in prep.)
- Results: point sources detected in <30% of PNe observed by Chandra (*not* including symbiotic Mira systems)
  - Typical sensitivities ~$10^{29\text{-}30}$ erg/s (or $L_x/L_{bol} \sim 10^{-5}\text{-}10^{-7}$)
  - Point X-ray sources are relatively hard
- Tentative conclusion:
  - Many (most?) PN cores are not magnetically active (at least not in the same sense as T Tauri stars), do not harbor close binary companions, & do not display strong star-disk interactions
  - In cases where pt. sources are present, mechanism is probably *not* shocks
    - accretion disks or mag. active binary companions

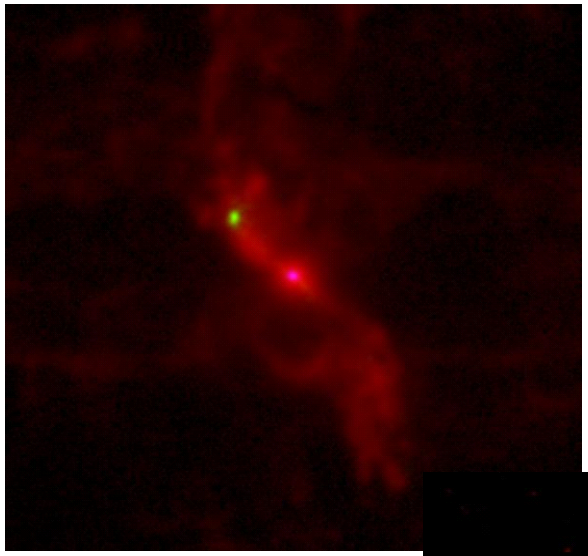
Representing the minority: NGC 6543 (the Cat's Eye)



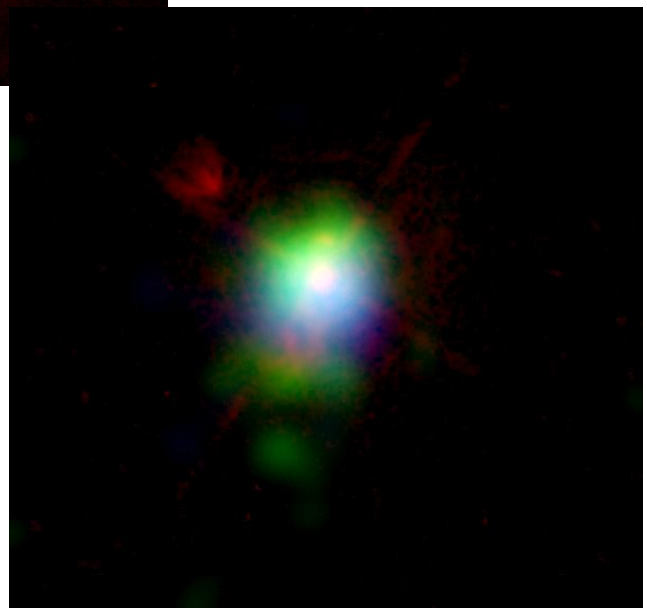
Left: Chandra X-ray image; right: Chandra (blue) on HST (red/green) (Chu et al. 2001)

In contrast: X-ray point sources are common (ubiquitous?) among symbiotic Miras

- AGB star plus (accreting) white dwarf
  - plus disk & jets?
- X-ray pt. sources detected in 5 of 6 systems
  - e.g., R Aqr, CH Cyg, Hen 2-104
  - Wide range of (highly variable) point source L_x
    - ~ 10^{28} erg/s to ~ 10^{32} erg/s
- Evidence for accretion of AGB wind material onto WD secondary



R Aqr (Chandra & NOT)



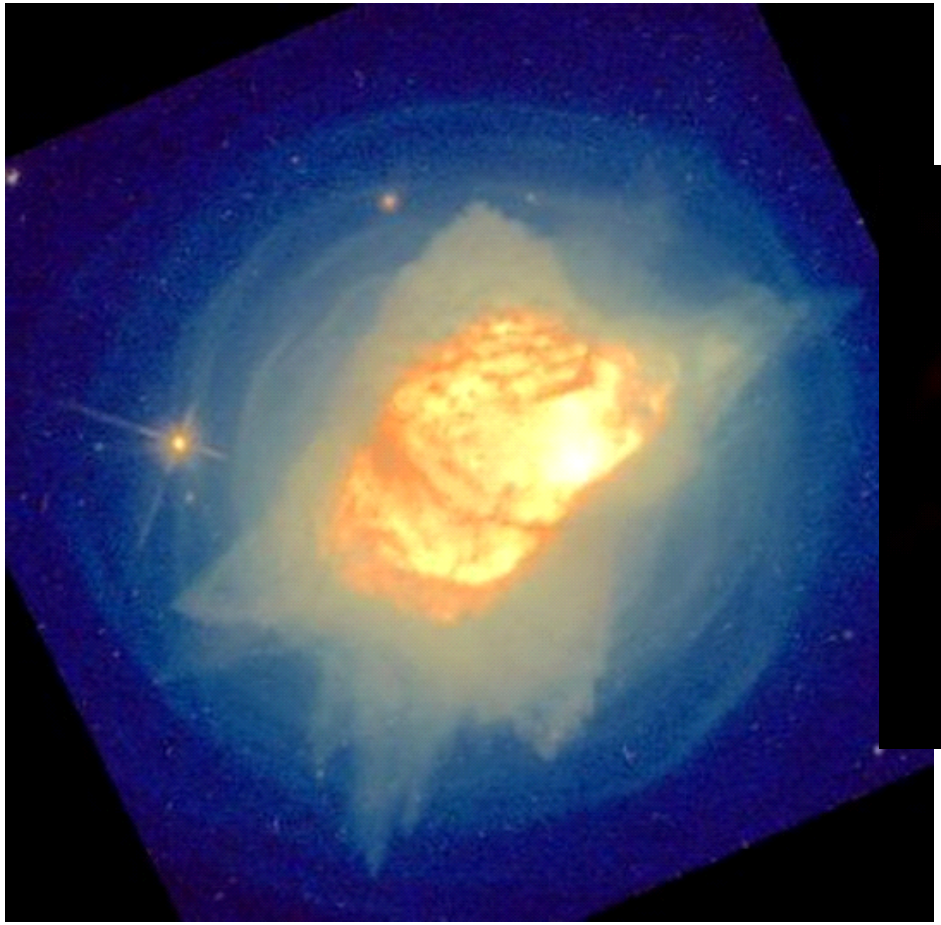
CH Cyg (Chandra & HST)

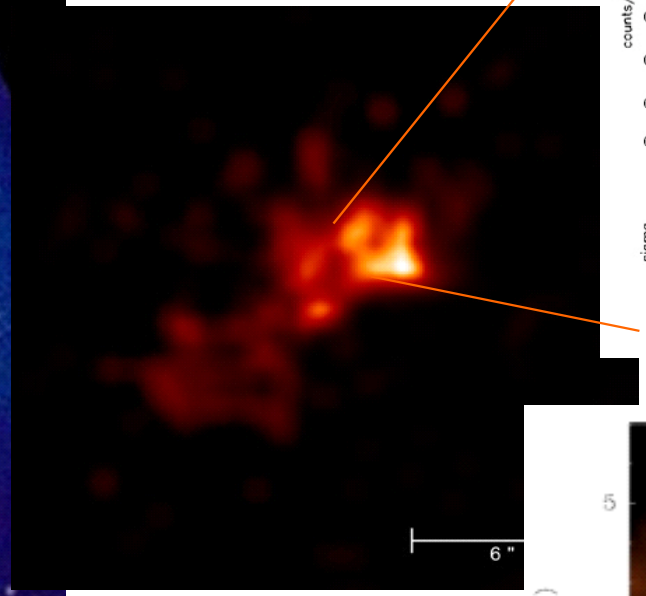
R Aqr & CH Cyg images: optical in red & X-ray in blue-green; see Galloway & Sokoloski (2004), Kellogg et al. (2007), Montez & Kastner (2008)

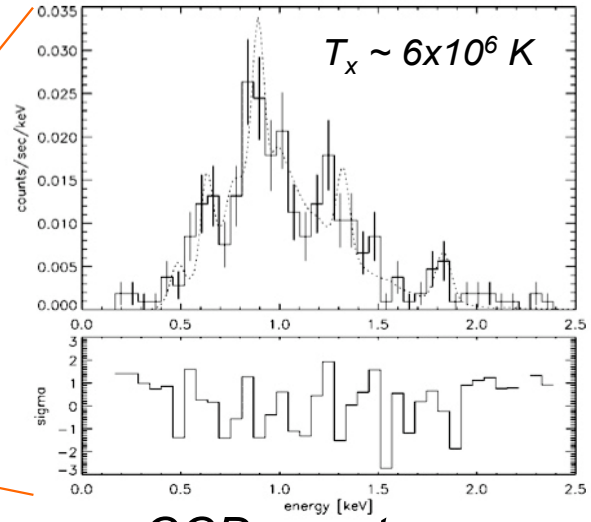
3) Detecting the elusive jets

- PNe and related objects observed thus far by Chandra & XMM that display jets and/or collimated flows in X-rays:
  - R Aqr, CH Cyg (symbiotic Miras)
  - NGC 7027
  - Menzel 3 (a candidate symbiotic Mira)
  - Hubble 5?

Chandra isolates collimated flows in NGC 7027



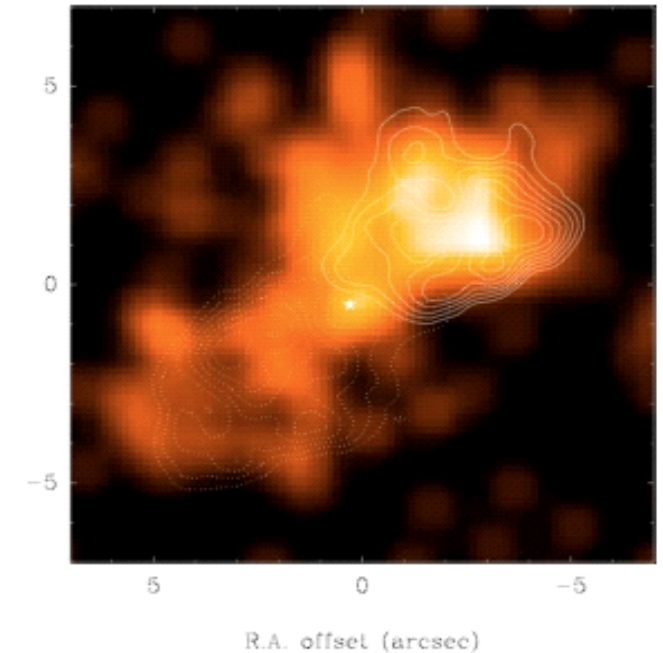




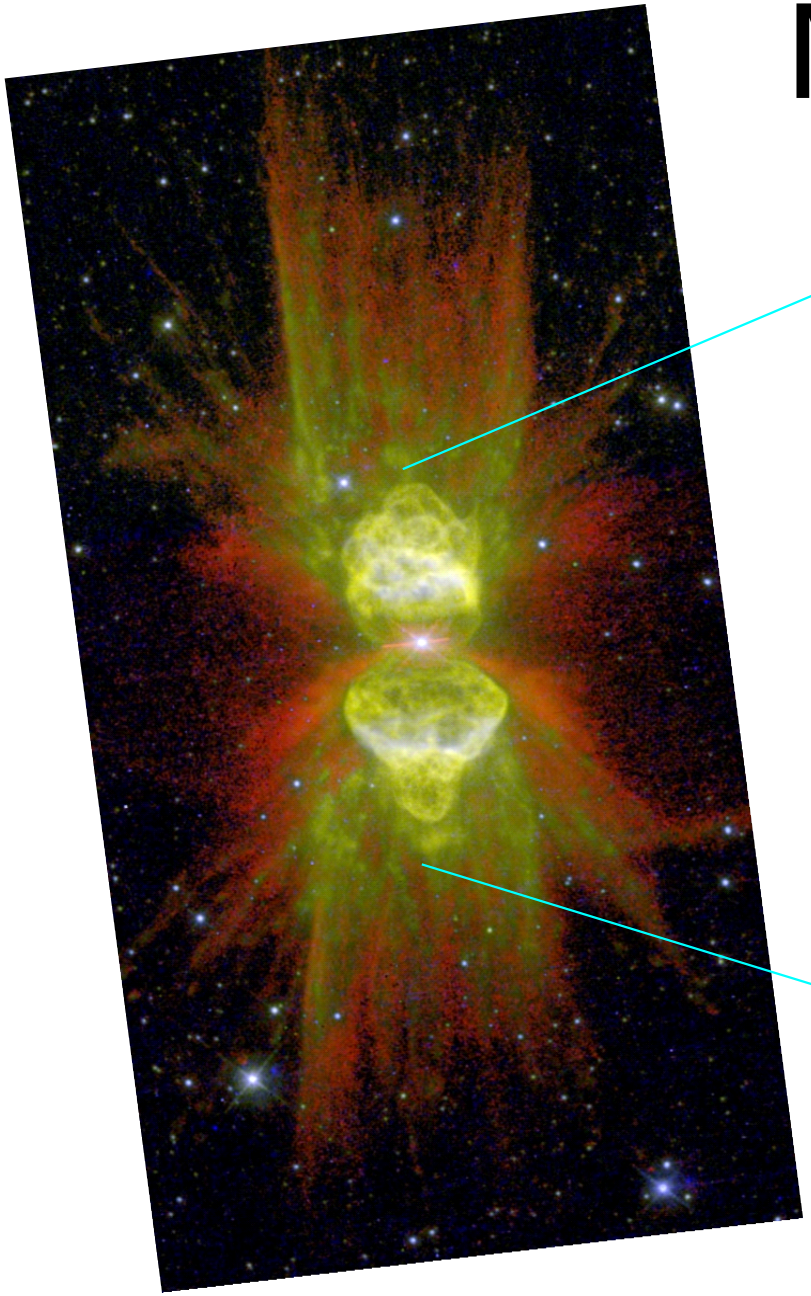
CCD spectrum

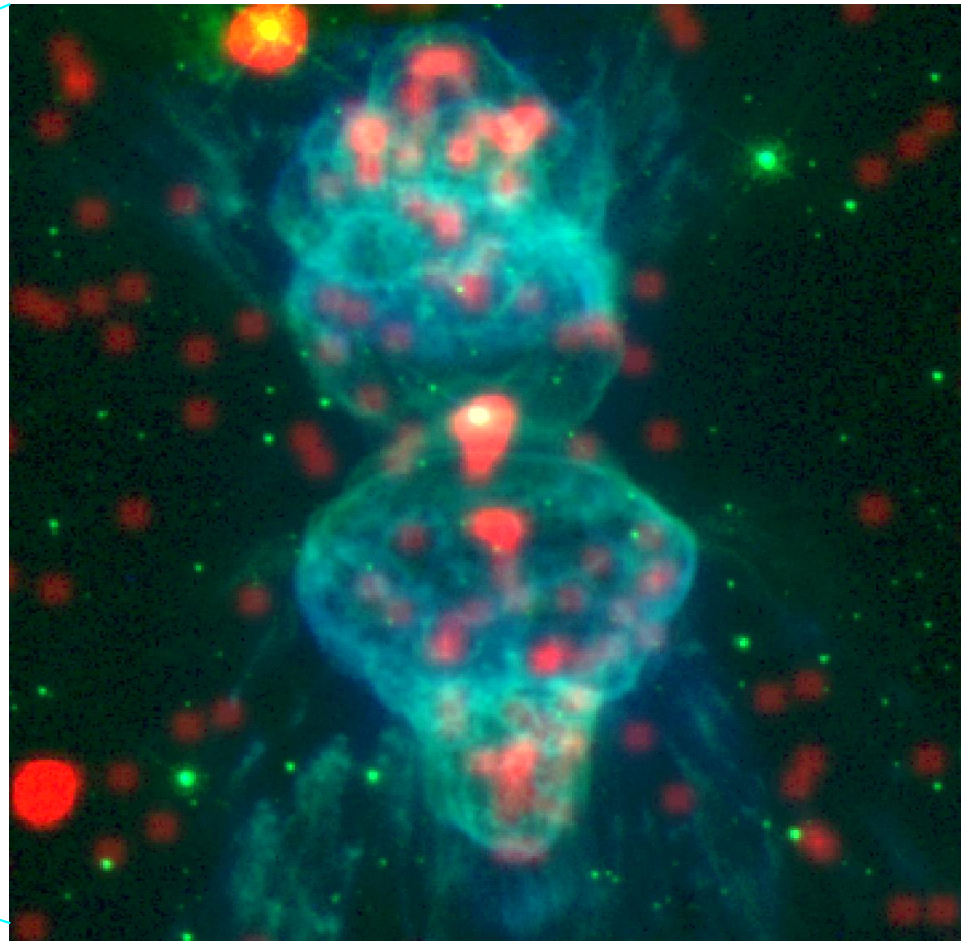
left: HST
middle: Chandra
(Kastner et al. 2001)

lower right: contours of high-v Br-gamma emission on Chandra
(Cox et al. 2002)



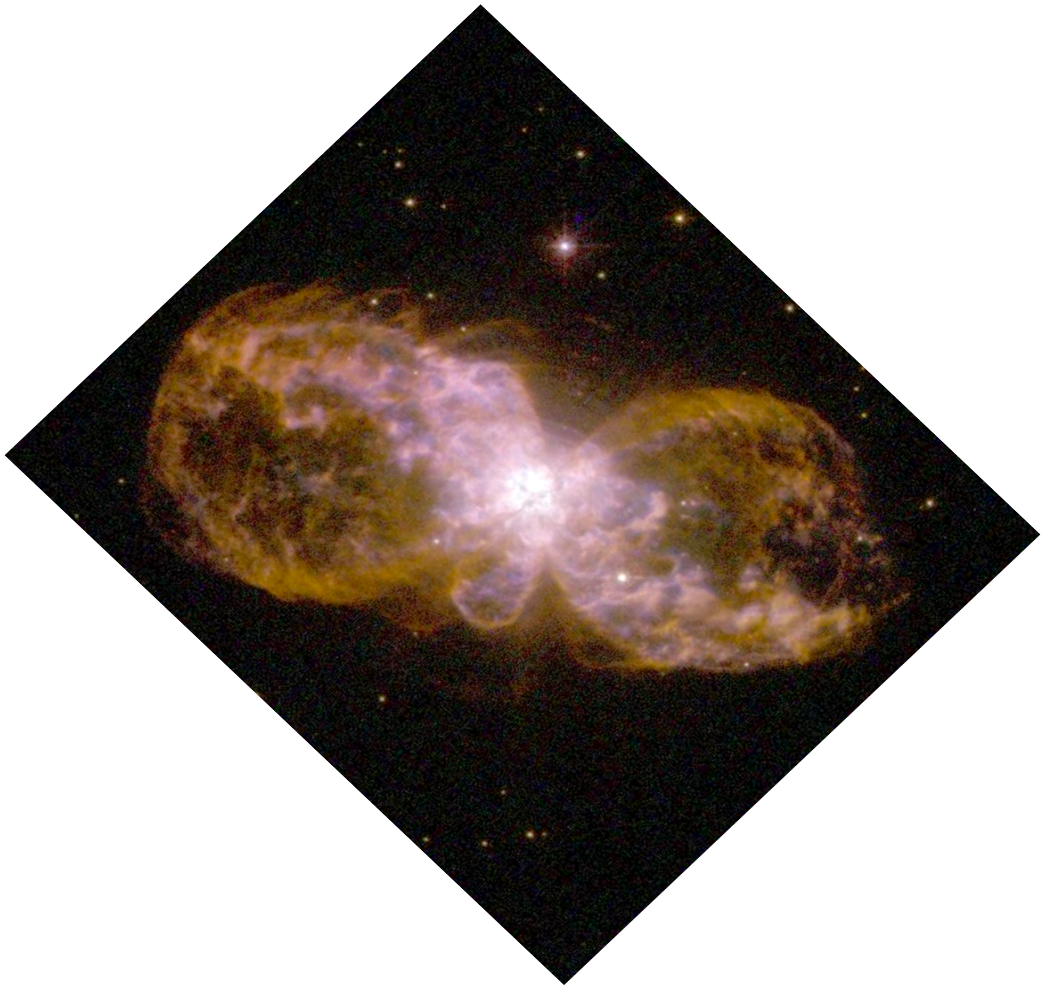
Chandra detection of jet(s) in Menzel 3

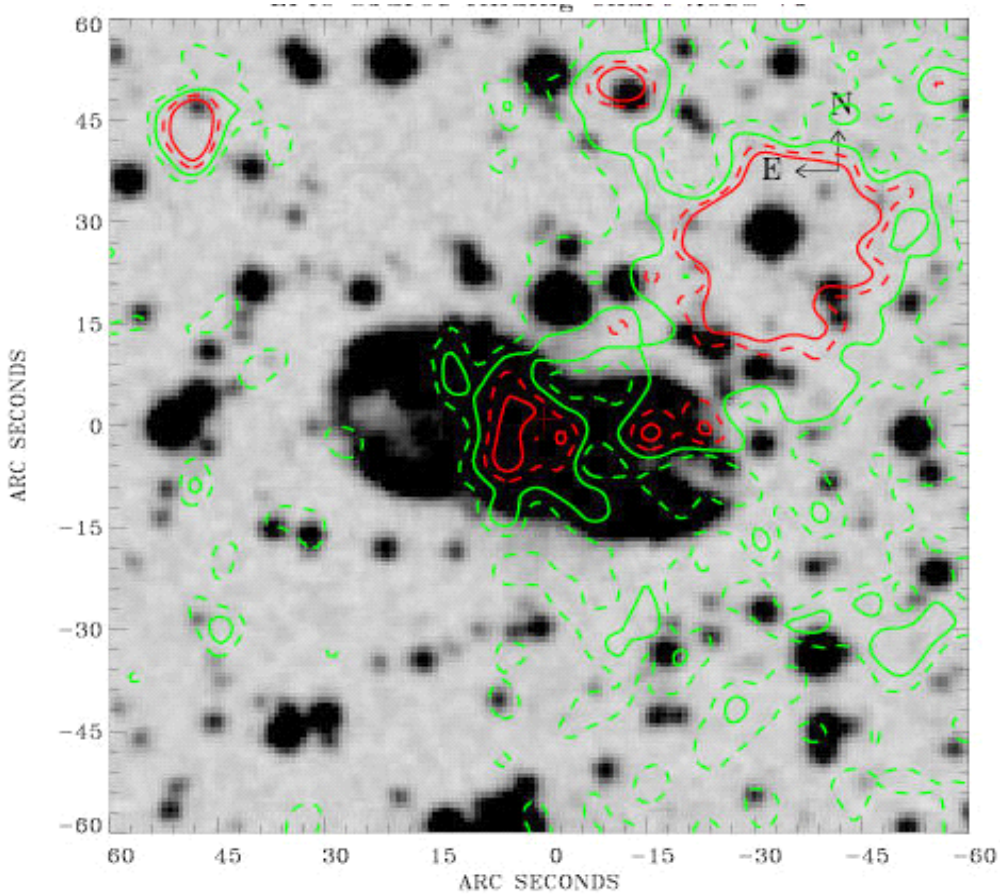




blue: HST; red: Chandra
(Kastner et al. 2003)

Serendipitous* XMM-Newton detection of jets in Hubble 5?

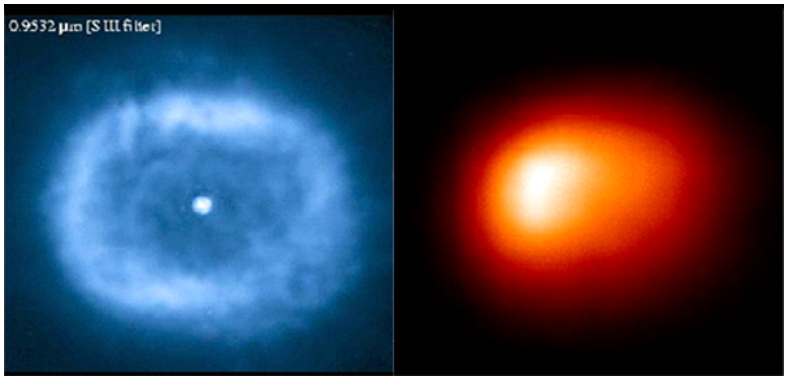




left: HST; right: XMM contours on DSS image (Montez, Kastner, et al. 2008, in prep.)

* *first results from NASA-funded XMM archival program to analyze all serendipitous observations of PNs*

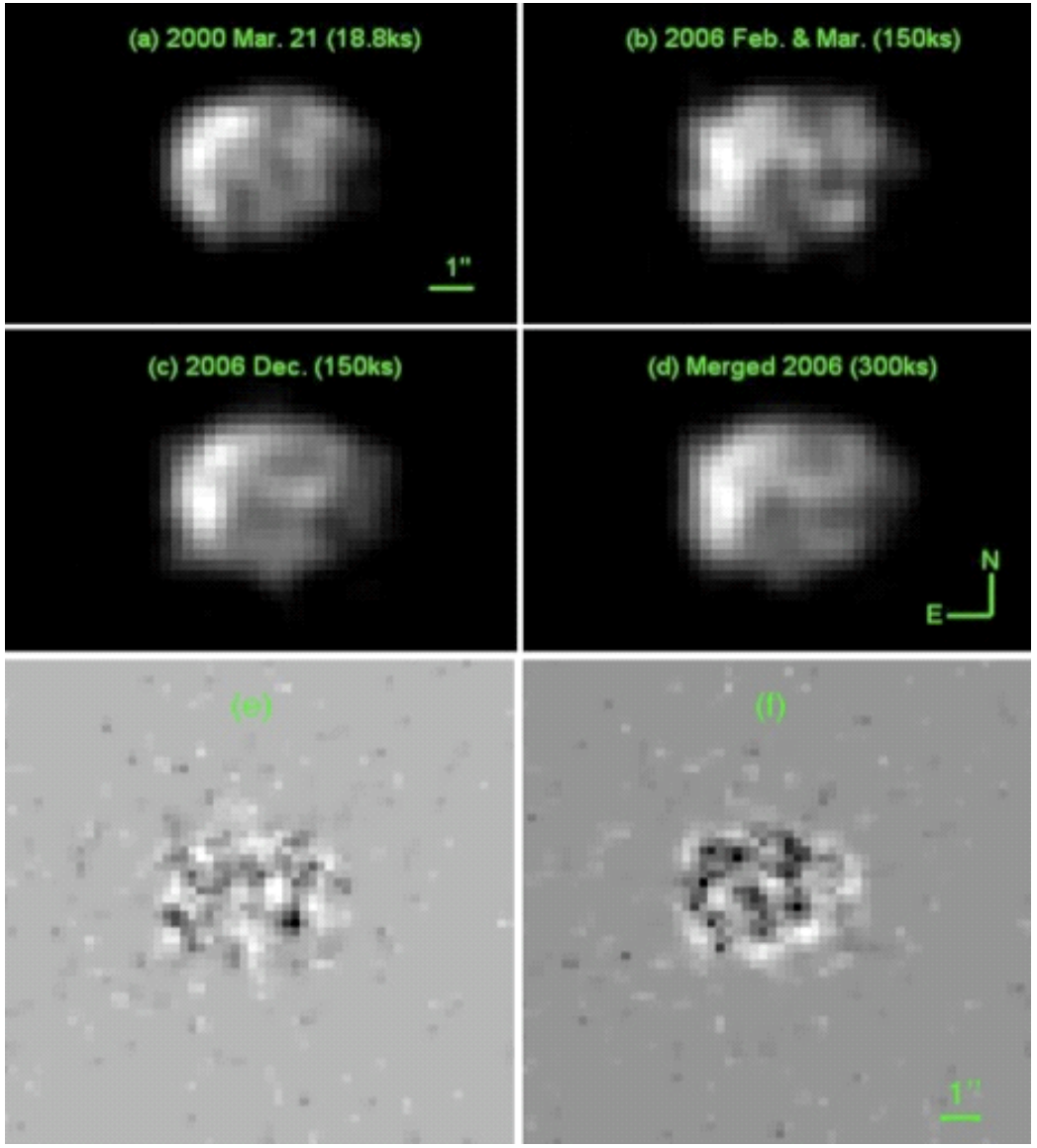
Measurable expansion of BD +30 3639 in X-rays?



Above: HST image and (original) CXO image

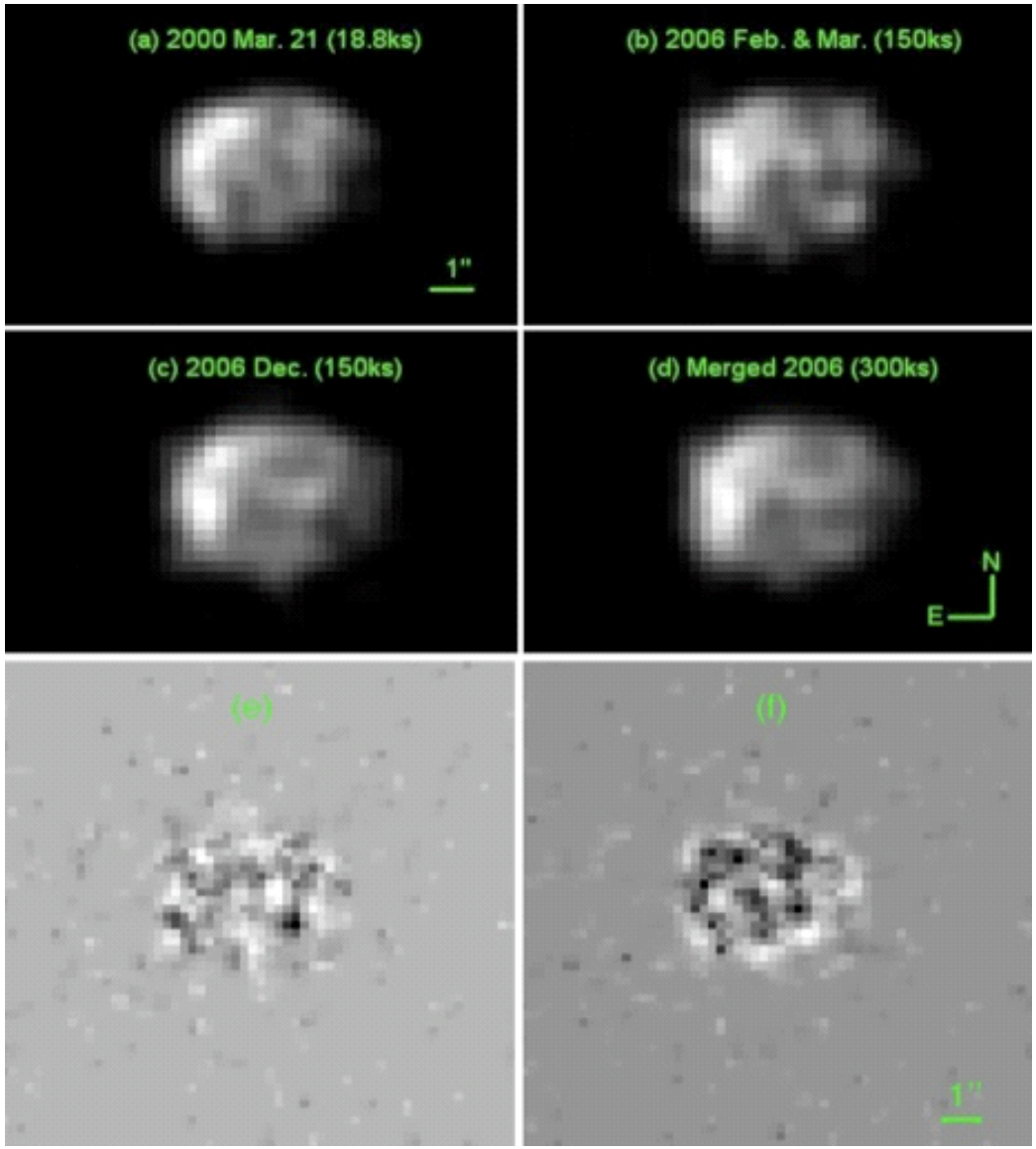
Right, top: 2000 and 2006 CXO images after subpixel event repositioning & deconvolution

Bottom: difference images, 2006(2)-2006(1) and 2006-2000

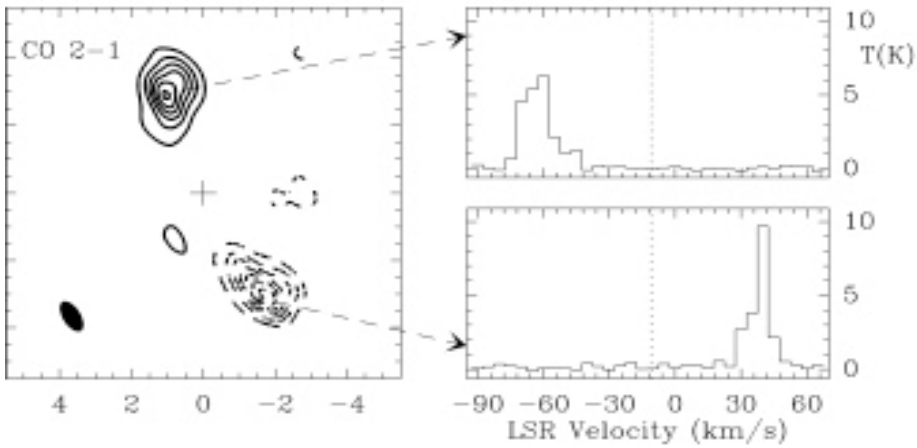


(Yu et al. 2008, in prep.)

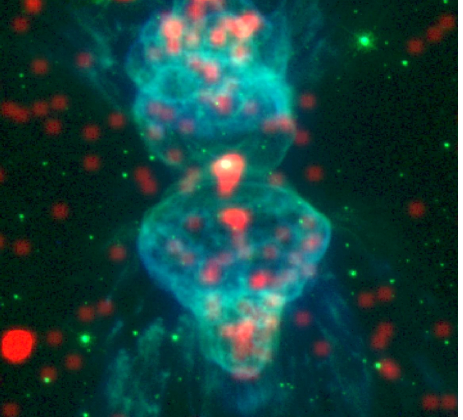
Is this apparent “hot bubble” related to the molecular “bullets” in BD +30 3639?



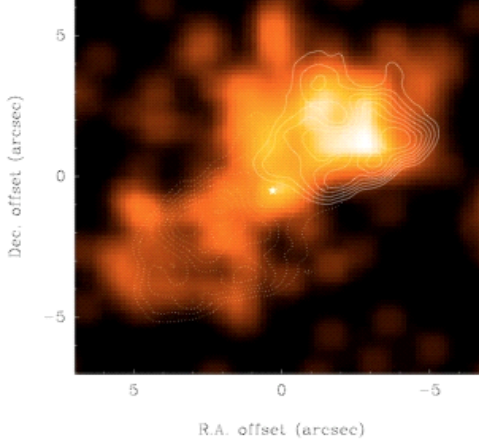
(Yu et al. 2008, in prep.)



IRAM PdB, CO(2-1)
(Bachiller et al. 2000)



Summary: PNe under X-ray scrutiny



1) Chandra and XMM-Newton imaging provides compelling evidence for PN shaping via wind-wind interactions
   - In many (probably most) cases in which X-rays are detected, X-rays emanate from “hot bubbles”
2) X-ray point sources implicate binary companions and accretion disks as likely agents of outflow collimation
   - pt. sources are rare in “classical” PNs, but common among symbiotic Mira systems
3) In some cases, X-rays also reveal the elusive PN jets themselves
   - Chandra followup programs I’d like to see in my lifetime:
     - Image jet-like structures seen in accidental, off-axis XMM detection of Hb 5
     - Perform X-ray expansion studies of NGC 7027 & BD +30 3639
     - Image additional symbiotic Miras