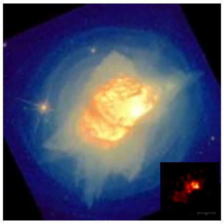
Volumetric 3D Modeling of the X-ray Emission Region within the Planetary Nebula BD+30°3639

Young Sam Yu[1], Joel H. Kastner[1], Daniel Dewey[2], Raanan Nordon[3], Ehud Behar[3,4], Noam Soker[3]

1. Center for imaging science, Rochester Institute of Technology, Rochester, NY 14623-5604
2. Kavli Institute, Massachusetts Institute of Technology, Cambridge, MA 02139
3. Department of Physics, Technion-Israel Institute of Technology, Haifa 32000, Israel
4. Senior NPP Fellow, Code 662, NASA/Goddard Space Flight Center, Greenbelt, MD20771

X-rays from planetary nebulae: key tests of stellar evolution and stellar wind interactions



What are planetary nebulae?

- Planetary nebulae (PN) are the last stages of evolution of intermediate mass (1-8 M_{solar}) stars.
- Planetary nebulae have terminated the asymptotic giant branch (AGB) stage; their central stars eventually evolve into white dwarfs.
- The fast wind (500-1500 km/s) from the central star of a PN may interact with a slow wind (10-20 km/s) originating with the former AGB star.
- What is the source of X-ray emission in certain PNs?

(Hot bubble generated by wind-wind interaction, collimated outflows, accretion/ejection of mass by companion star, etc…)

Fig. 1. NGC 7027: It appears the spherical AGB outflow is being disrupted by fast, collimated outflows from the ~200 kK central star. *Inset*: Chandra X-ray image of NGC 7027 (Kastner et al. 2001), showing X-ray-emitting shocks that result from this wind interaction.

Construction of Volumetric 3D Plasma Model of BD+30°3639

Background and Goals

PN shaping process remains poorly understood because the variety of shapes develops over a very short timescale

- Investigate the intrinsic density/temperature structure of X-ray emitting gas
- Investigate its orientation with respect to the line of sight.
- Provide deep insight into the shaping origin and process in PN and the nature of their progenitors.

Approach

- Volumetric 3D modeling (V3D*) code, currently developed by MIT's Kavli Institute, encodes source geometry in 3D cubes of scalar values and these can then be used for visualization and as input to simulations.
- This method enables the comparison of user-defined 3D models with observed 2D event-based data sets, considering all available information such as sky X, Y positions, dispersed images, and radial and energy distributions. Chandra's instrumental characteristics are also applied.
- Detailed process is shown in Fig. 2.

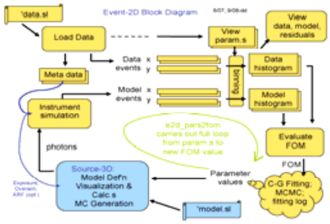


Fig. 2. Event 2D Block Diagram. Adopted from http://space.mit.edu/hydra/E2D_demo/e2d_demo.html

High-resolution X-ray Imaging and Spectroscopy of BD+30°3639

- We observed the X-ray bright, young PN, BD+30°3639 in 2006 (February, March & December) for 300 ks using the Chandra X-ray Observatory's Low Energy Transmission Gratings in combination with its Advanced CCD Imaging Spectrometer (LETG/ACIS).
- We used ISIS** to construct a series of APED** plasma emission models for a range of values of intervening absorbing column (NH), then varied the plasma temperature and abundances to fit the observed 1st-order spectrum.

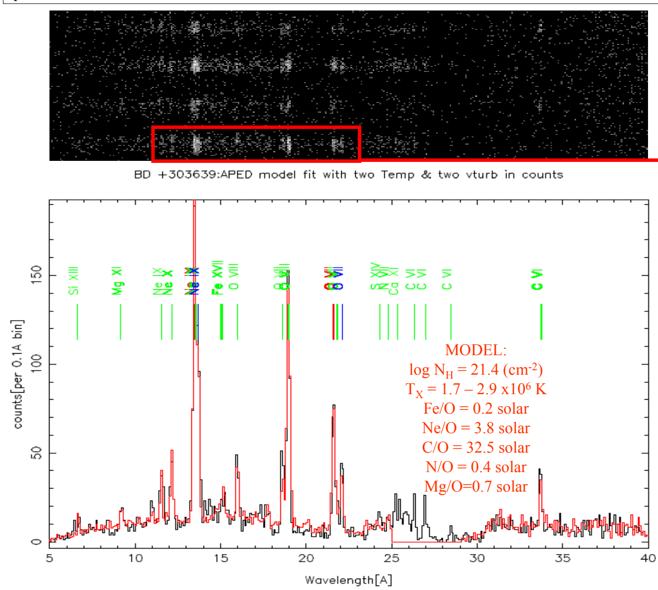


Fig. 3. Dispersed spectral images of BD+30°3639 from 5 to 40 Å for positive and negative first-order from first (Feb+Mar; Lower Two) and second (Dec; Upper Two) epoch of 2006 (**Top**). Combined counts spectrum of BD+30°3639 (including background) overlaid with the best-fit two-component APED** model (**Bottom**). **Inset:** Spectral plasma model fitting results (Yu et al. 2009).

RESULT

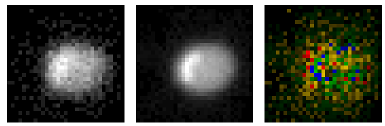


Fig. 4. 0th order image vs. reconstructed image
CXO 0th order X-ray image (**left**), Reconstructed 2D image (**middle**) and Residual Image (**right**).

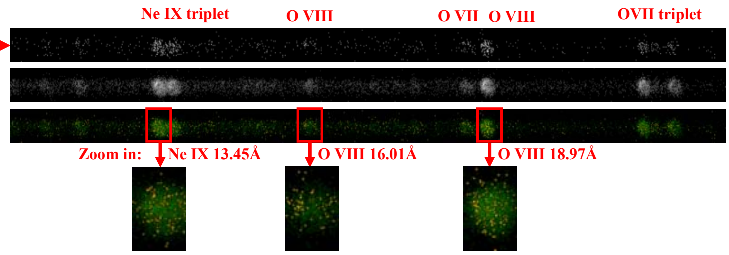


Fig. 5. Dispersed Image vs. reconstructed image
Dispersed X-ray image in the range of 11-23 Å (**top**), Reconstructed 2D image (**middle**) and Residual Image (**bottom**). In the residual images,
blue indicates: chi < -1.5 [model is much greater], green indicates: -1.5 < chi < 0 [model is greater]
yellow indicates: 0 < chi < 1.5 [data is greater], red indicates: chi > 1.5 [data is much greater]

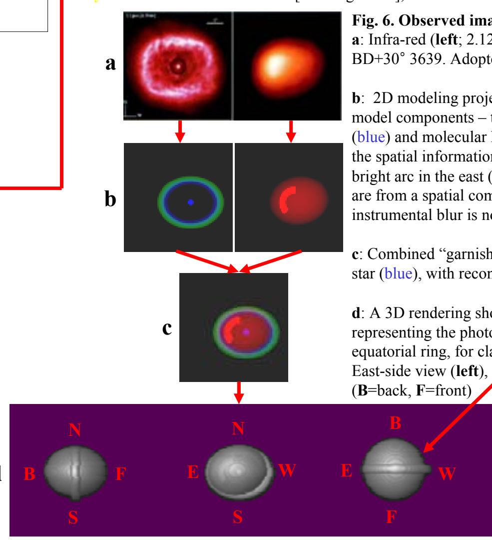


Fig. 6. Observed image vs. 2D modeling image projected on the sky
a: Infra-red (**left**; 2.12 um) and X-ray (Chandra ACIS, **right**) images of BD+30° 3639. Adopted from Kastner et al. 2000

b: 2D modeling projected on the sky. The "non-X-ray" (or "garnish") model components – the WC-type central star (blue), photoionized PN gas (blue) and molecular hydrogen emission (green) - are generated based on the spatial information described in Li et al. 2002 (**left**). Hot bubble and bright arc in the east (**right**) are generated by the V3D code; parameters are from a spatial comparison with the observed X- ray image. Note that instrumental blur is not included at this modeling stage.

c: Combined "garnish" image, nebular gas (blue and green) and central star (blue), with reconstructed 2D X-ray image (**right**; Red).

d: A 3D rendering shows the hot bubble spheroid; the non-X-ray 'garnish' representing the photoionized and molecular PN gas is here limited to an equatorial ring, for clarity
East-side view (**left**), front view (**middle**) and top (north) view (**right**)
(**B**=back, **F**=front)

References
Kastner, J. et al. 2000, ApJ, 545, L57
Kastner, J. et al. 2001, ApJ, 550, L189
Li et al. 2002, AJ, 123, 2676
Yu et al. 2009, ApJ, 690, 440

*V3D is available via http://space.mit.edu/hydra/v3d.html
**ISIS and APED are available via http://space.mit.edu/CXC/ISIS

Conclusions and Future Work

The results show:
* V3D's capability to reproduce the key geometric components within this object
* The potential for V3D-based modeling to specify the detailed structure of the X-ray-emitting hot bubble within BD+30°3639, as well as the nebula's other key (optical and IR) emission components.

Ongoing work includes:
* Implementing a spatially-varying X-ray absorption (N_H) 'screen'
* Using archival HST images to constraining the N_H 'screen' and the optical/IR 'garnish' components
* Using V3D to test the possibility of proper motion of the X-ray-emitting gas (as inferred from multi-epoch Chandra imaging)
* Using PN wind-collision models to constrain the density structure adopted for the V3D simulations