Extended X-ray Jets in Radio-loud Quasars: A Morphological Study

By Suresh Parekh

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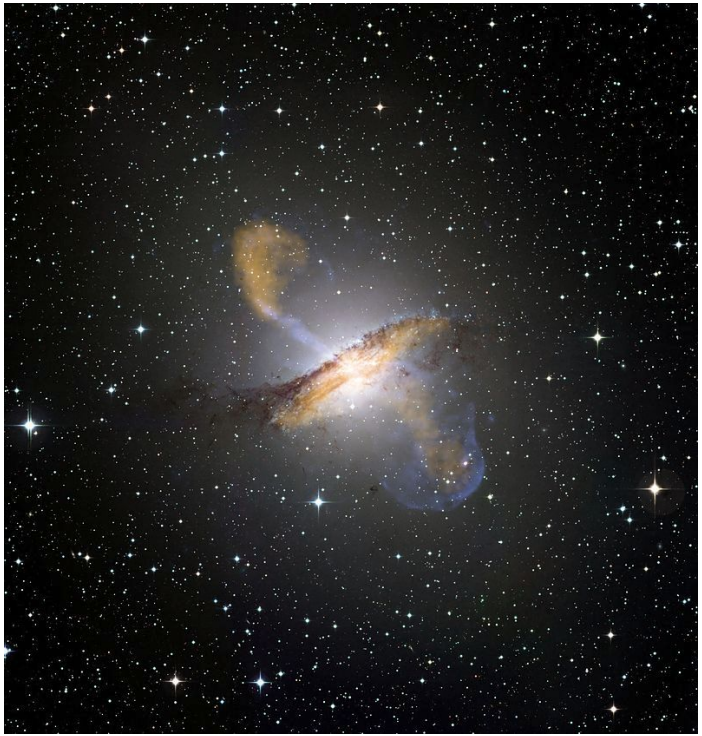
Active Galactic Nuclei

- An Active Galactic Nucleus (AGN) is a compact region at the center of a galaxy that has a much-higher luminosity than that of a normal galaxy ($>10^{40}$ erg/s).
- The observed emission covers the whole electromagnetic spectrum.
- Active galactic nuclei are the most luminous persistent sources of electromagnetic radiation in the universe.



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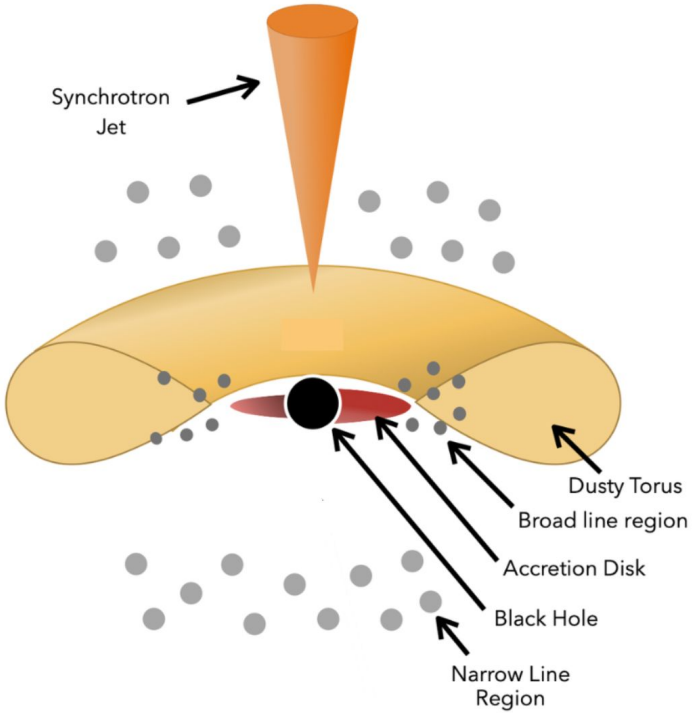
AGN Components

1. **Central Supermassive Black Hole**
2. **Accretion Disk**
3. **Broad Line Region or BLR**
4. **Narrow Line Region or NLR**
5. **Molecular Torus**
6. **Relativistic Jets**



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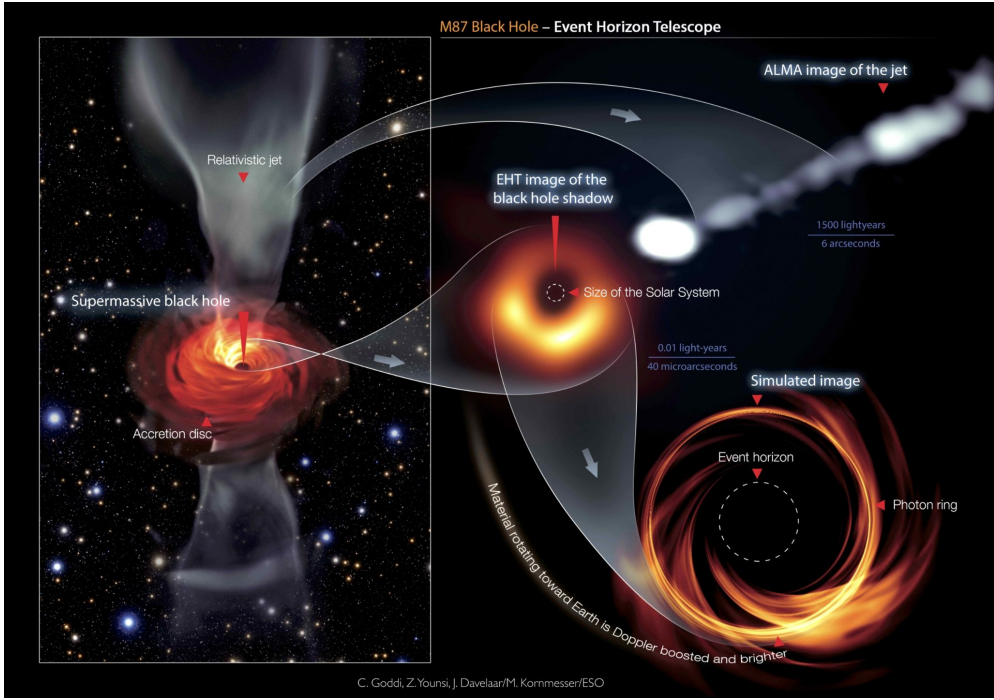

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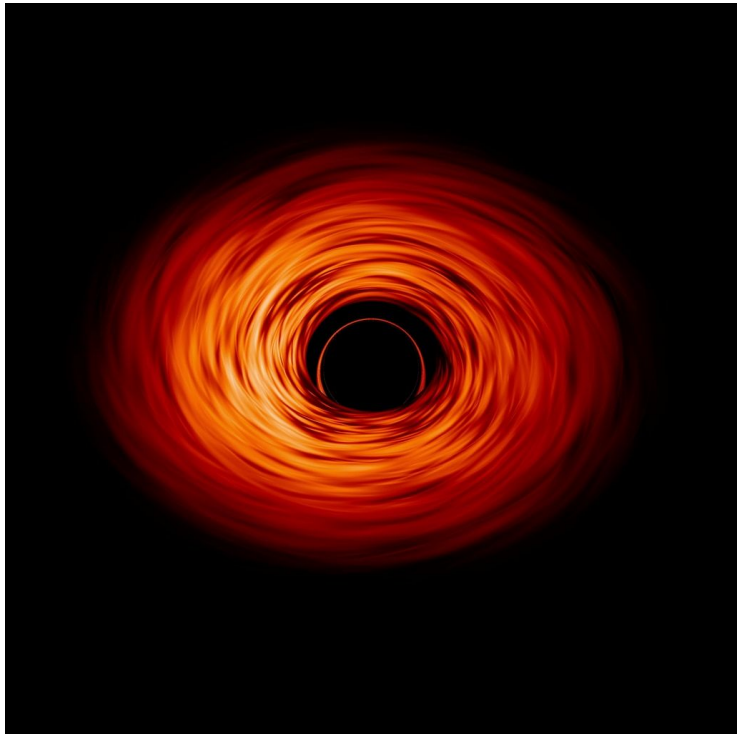

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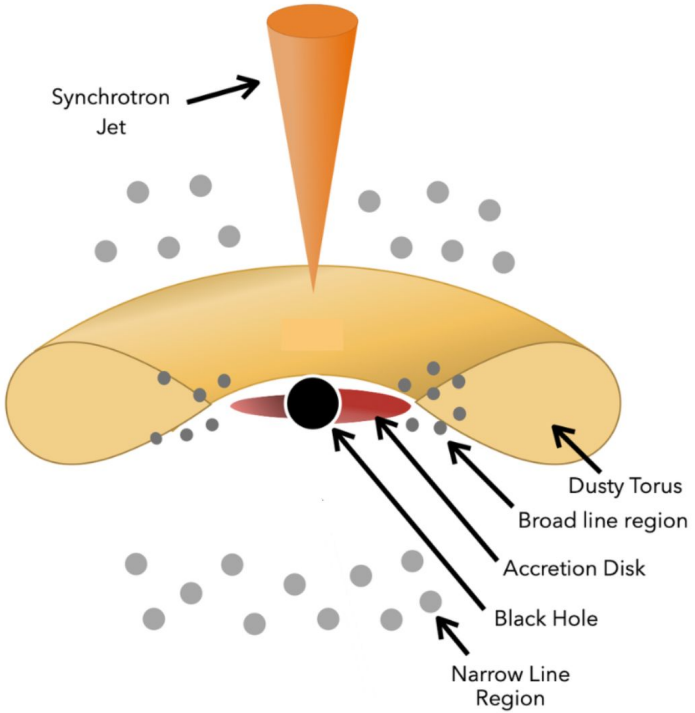

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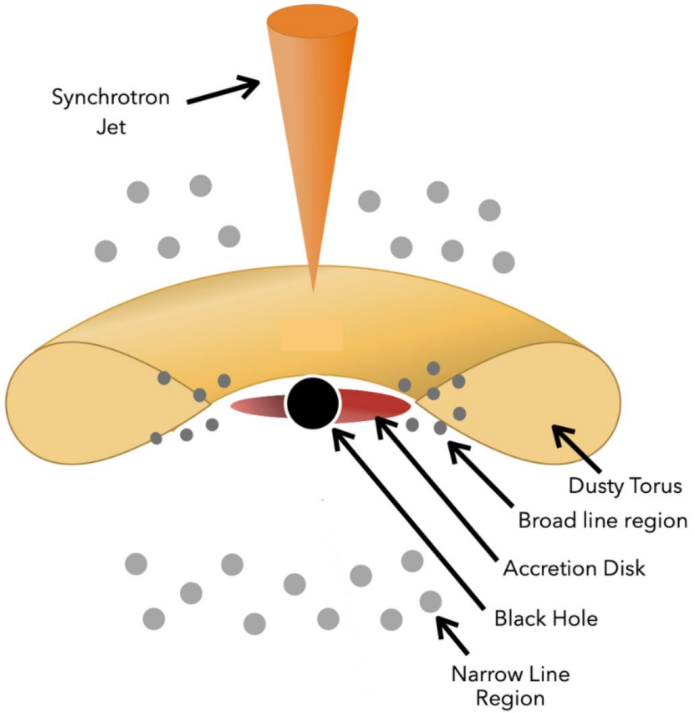

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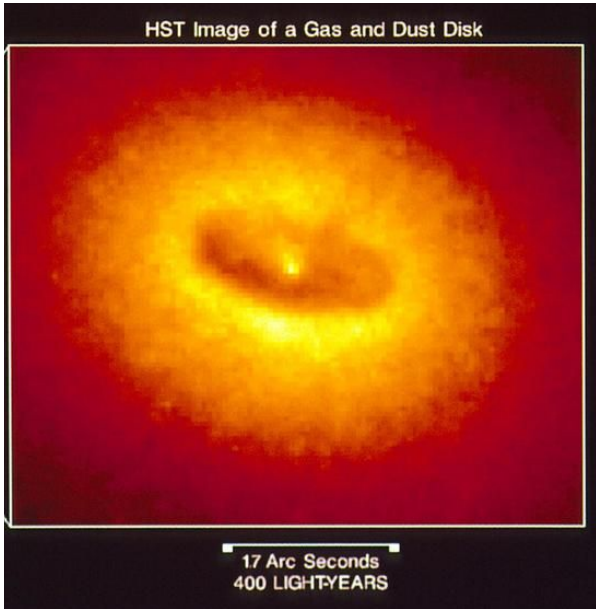

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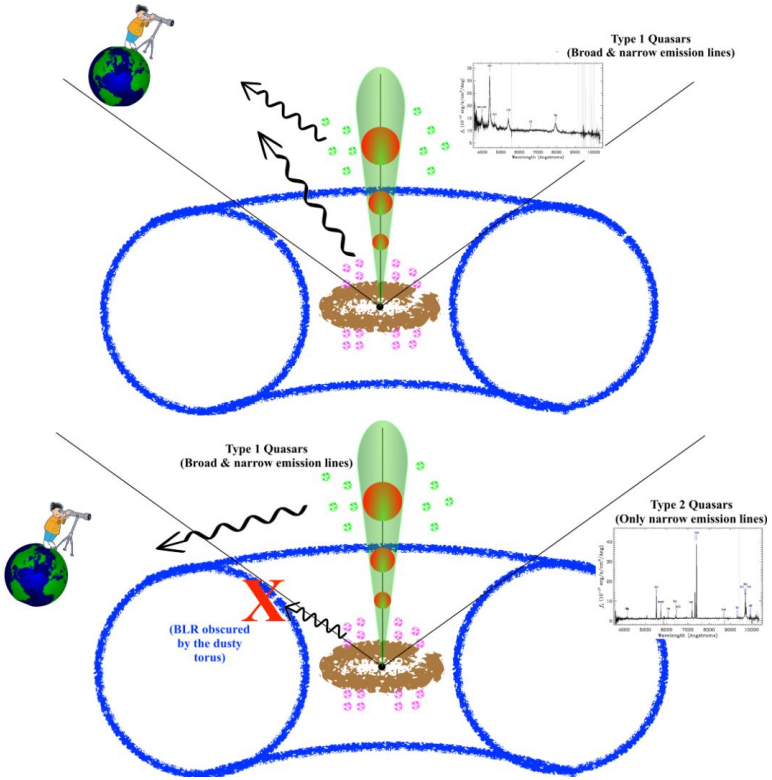
6. **Relativistic Jets**

Image Credits: NRAO

AGN Classification

- **Radio Loud AGN**
  - Radio Loud Quasars
  - Blazars
    - Optically Violent Variables (OVVs)
    - BL Lac Object
  - Radio Galaxies
- **Radio Quiet AGN**
  - Radio Quiet Quasars
  - Seyfert Galaxies
  - Low Ionization Nuclear Emission line Regions (LINERs)



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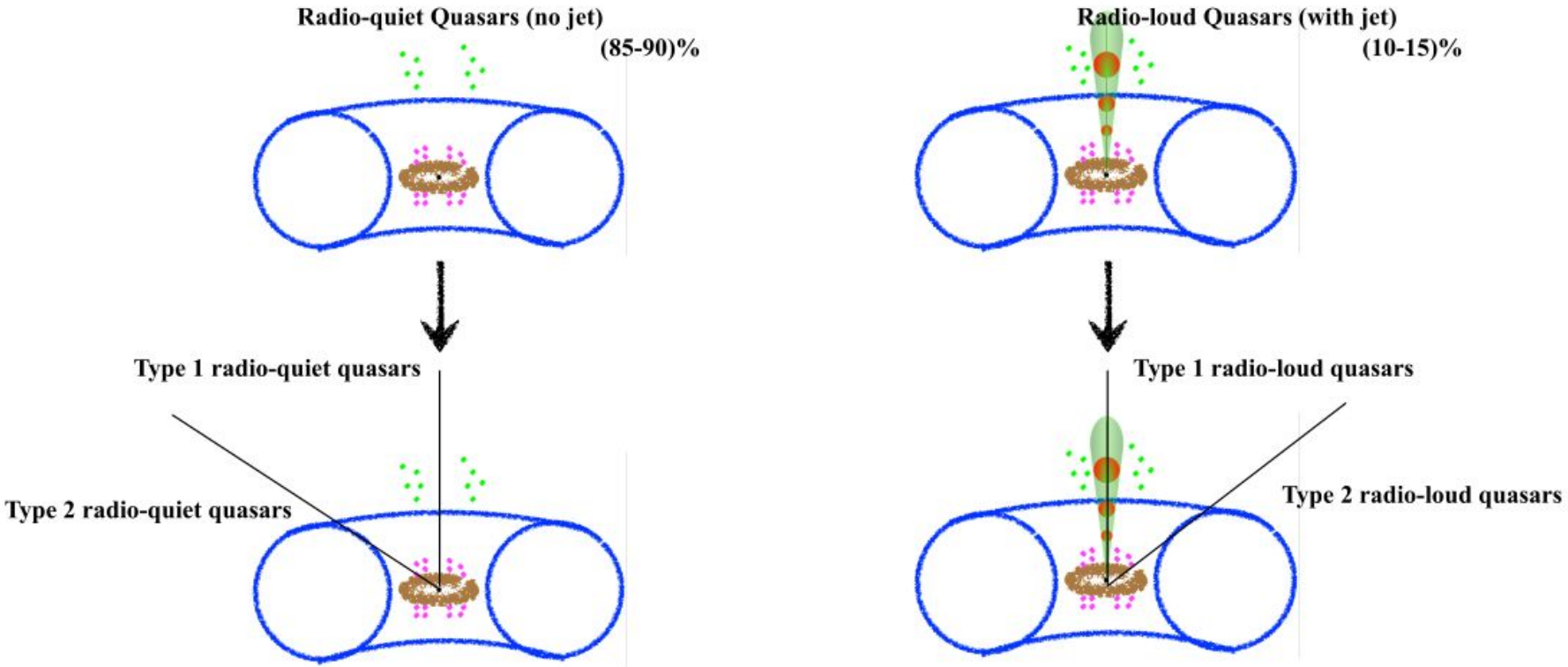
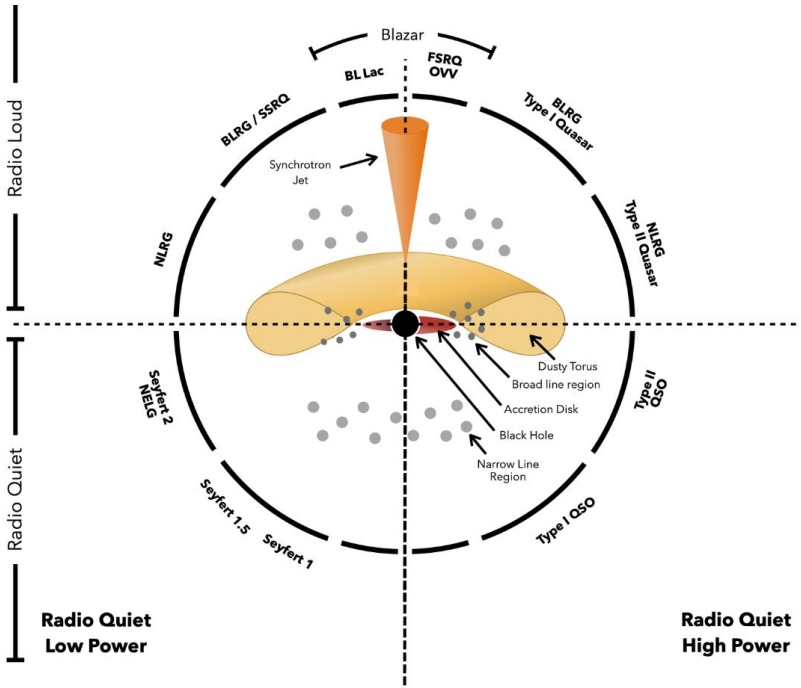
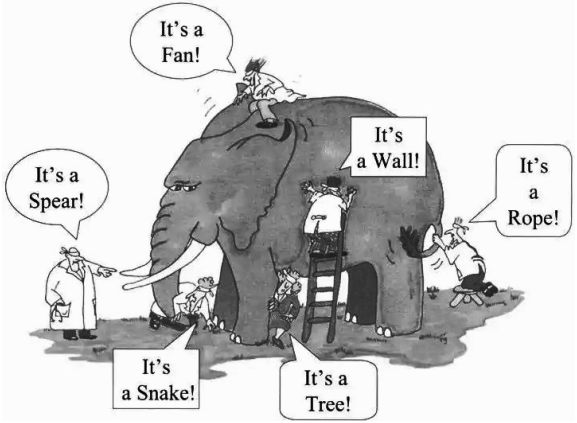


AGN Unification



Radio Loudness	Optical Emission Line Properties		
	Type 2 (Narrow Line)	**Type 1** (Broad Line)	**Type 0** (Unusual)
Radio-quiet:	Seyfert 2	Seyfert 1 QSO	
Radio-loud:	NLRG { *FR I*, *FR II* }	BLRG SSRQ	Blazars { *BL Lacs*, (*FSRQ*) }
	decreasing angle to the line of sight ⟶		



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Motivation & Goal

Statistically Detect Jets in High redshift Quasars

Chandra X-Ray Observatory and ACIS Chip

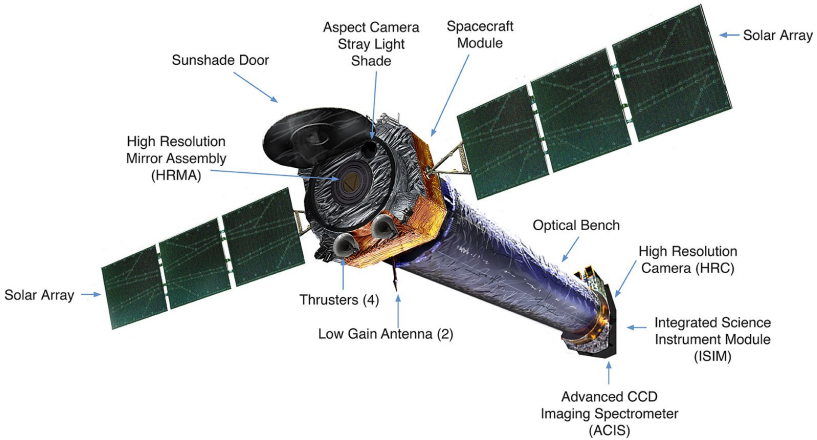
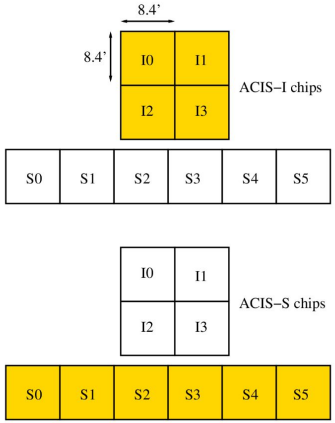


Image Credits: *Chandra Archive*



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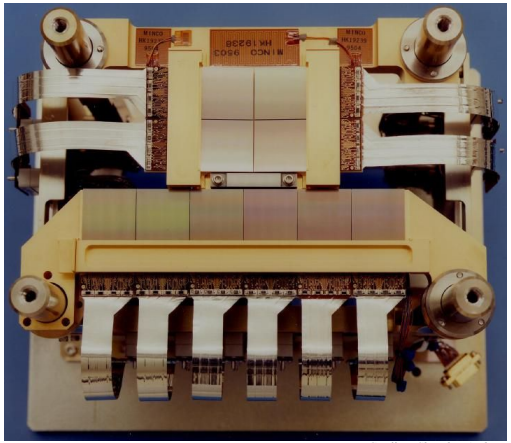


Image Credits: *Chandra Archive*

Chandra Interactive Analysis of Observations


```
(ciao) suresh@suresh:~$ ciaover
# packages in environment at /home/suresh/miniconda3/envs/ciao:
#
# Name                    Version                   Build  Channel
caldb_main                4.10.2                        0    https://cxc.cfa.harvard.edu/conda/ciao
ciao                      4.15.1          py310h50a7cbf_0    https://cxc.cfa.harvard.edu/conda/ciao
ciao-contrib              4.15.1                    py_1    https://cxc.cfa.harvard.edu/conda/ciao
ds9                       8.4.1                         0    https://cxc.cfa.harvard.edu/conda/ciao
sherpa                    4.15.0          py310h3fd9d12_0    https://cxc.cfa.harvard.edu/conda/ciao

System information:
Linux suresh 5.15.0-67-generic #74~20.04.1-Ubuntu SMP Wed Feb 22 14:52:34 UTC 2023 x86_64 x86_64 x86_64 GNU/Linux
```

Methodology

1. **Fetching the Data from Chandra Archive:**

   The download_chandra_obsid tool will download the data for the given Chandra Observation Id (ObsId) from the public archive.

Methodology

2. Reprocessing the Data:

Always reprocess

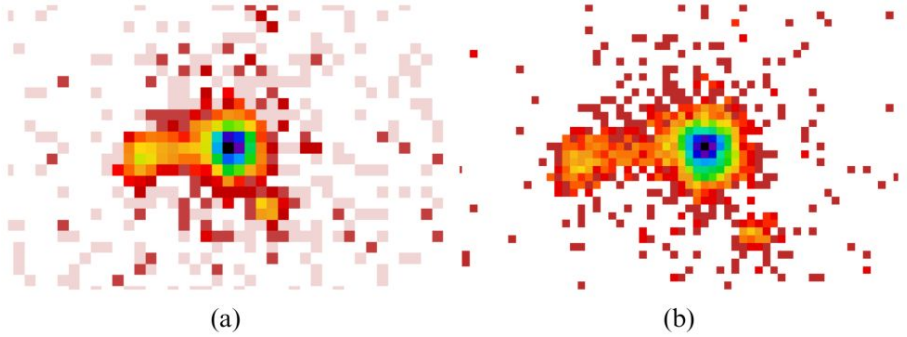
The CXC strongly encourages users to reprocess their data to ensure that they have the latest calibrations consistent with the current CALDB.

Users should run `chandra_repro` or follow the step by step instructions the Reprocessing Data to Create a New Level=2 Event File thread.

```
(ciao) suresh@suresh:~$ chandra_repro 12056
```

Methodology

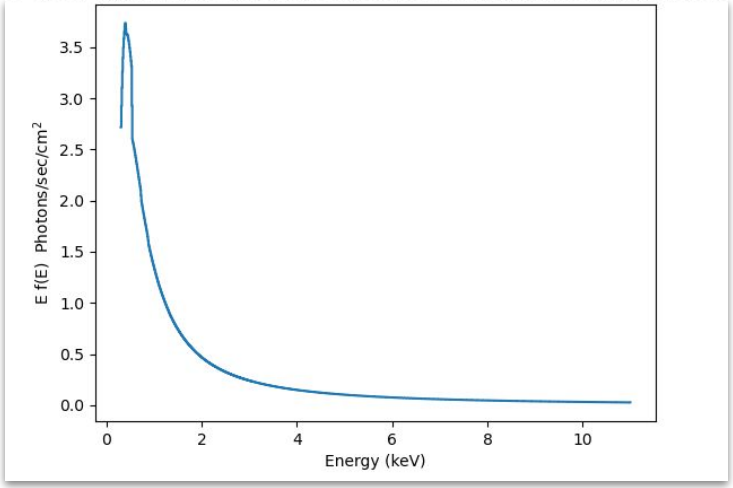
3. **Making Exposure corrected image:** The flux_obs script takes a stack of event files, creates exposure maps for each observation, and divides the resulting images to produce a coadded, exposure-corrected image. This process can be done for one or more energy bands.

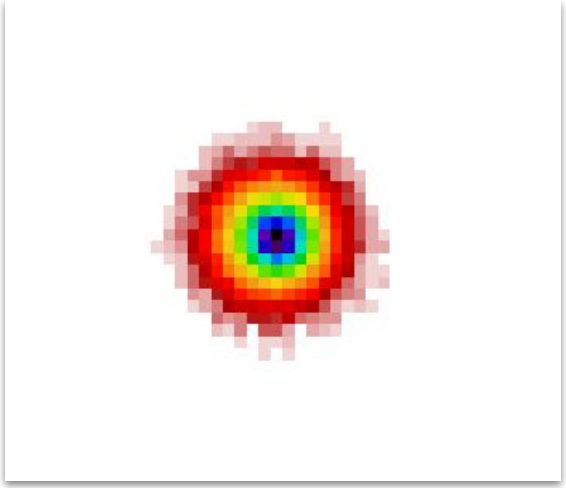


(a) Raw 0.5-7 keV image of quasar PKS 065-08, (b) exposure corrected and binned to 0.492 arcsec image of quasar PKS 065-08

Methodology

3. **Generating Spectrum and PSF:** The point spread function (PSF), describes the shape and size of the image produced by a delta function (a point) source.



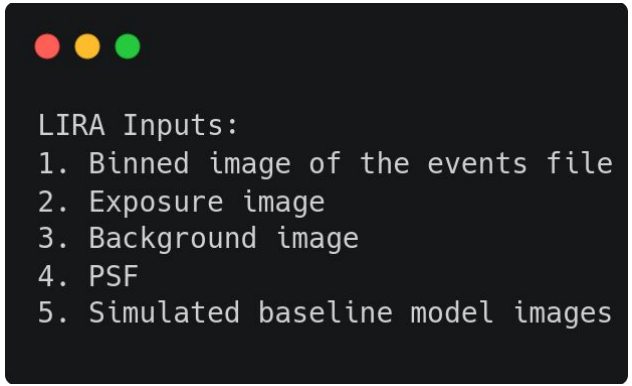


Methodology

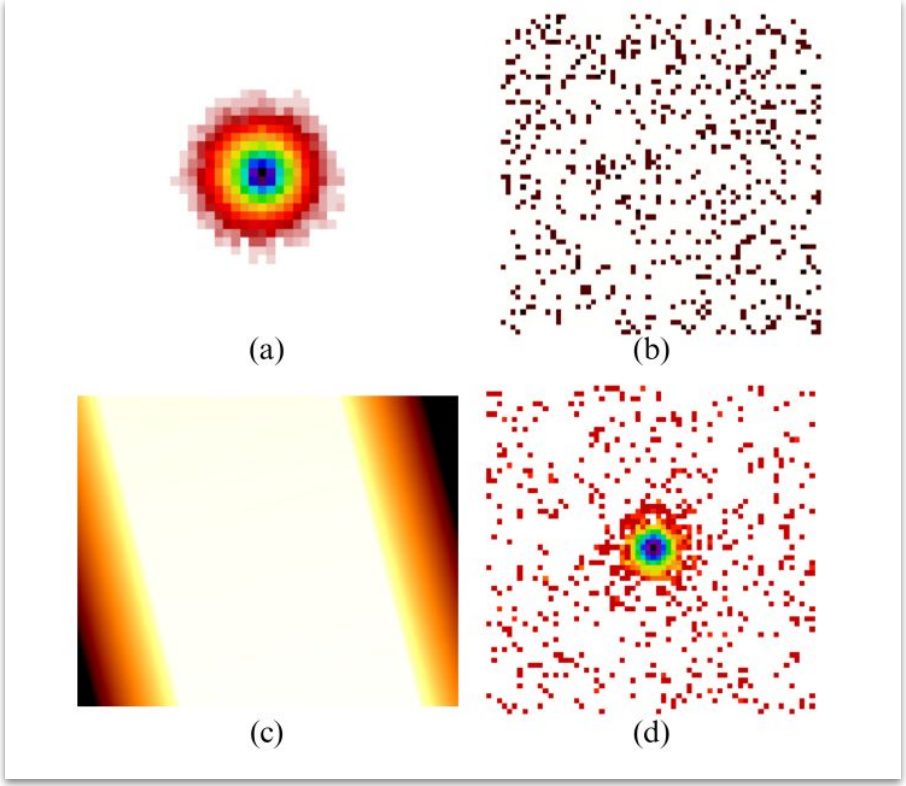
- MARX is a suite of programs created and maintained by the MIT/CXC/HETG group and is designed to enable the user to simulate the on-orbit performance of the Chandra X-ray Observatory. marx provides a detailed ray-trace simulation of how Chandra responds to a variety of astrophysical sources and can generate standard FITS event files and images as output.

Methodology

5. **Running LIRA:** The psf generated, binned images and the energy spectra has to be given input to the Low-counts Image Reconstruction and Analysis (Low-counts Image Reconstruction and Analysis (LIRA) which runs Markov Chain Monte Carlo (MCMC) simulations and provide non-Poisson deviations from the baseline model, that indicates jets emitting from the X-ray Quasar.

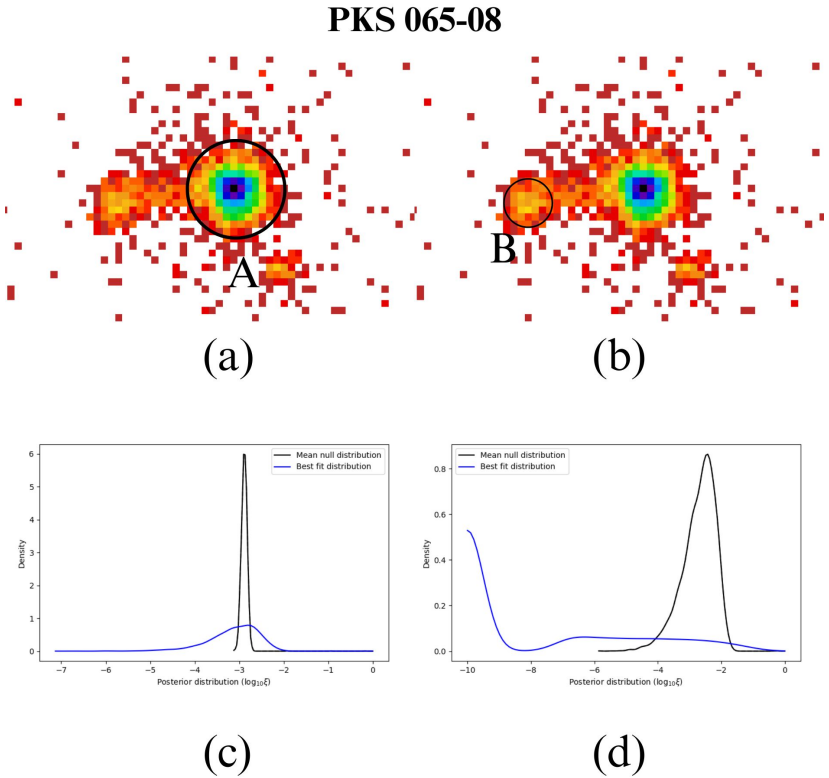


Methodology



(a) PSF of PKS 065-08 generated by marx,
(b) background image of PKS 065-08,
(c) Exposure image of PKS 065-08,
(d) Simulated baseline model for PKS 065-08 using fake function.

Results



Images, regions of interest (ROIs), and results for quasar PKS 0605-08.

- (a,b) The observed Chandra ACIS-S image with colors indicating photon counts with fitted regions of Interests A and B. A is the center core region and B is the jet region.
- (c,d) The posterior distributions of ξ in each ROI for the data (blue solid curve), the average of 50 simulated replicate images under the null model, which includes the quasar and a background but not a jet (black solid curves).

References

- Jessica Thorne, Aaron Robotham, Luke Davies, and Sabine Bellstedt. Agn unification diagram, March 2022. URL https://doi.org/10.5281/zenodo.6381013. Was originally created to be included in the introduction of Thorne J. E., et al., 2022, MNRAS, 509, 4940.
- Wikipedia contributors. Seyfert galaxy — Wikipedia, the free encyclopedia. https://en.wikipedia.org/w/index.php?title=Seyfert_galaxy&oldid=1146778964, 2023. [Online; accessed 2-May-2023].
- F. D. Drake. Radio astronomy: ¡i¿galactic and extra-galactic radio astronomy¡/i¿. gerrit l. verschuur, kenneth i. kellerman, and virginia van brunt, eds. springer-verlag, new york, 1974. Xii, 402 pp., illus. $37.80. Science, 188 4187):444–444, 1975. Doi: 10.1126/science.188.4187.444.a. URL https: //www.science.org/doi/abs/10.1126/science.188.4187.444.a. Thomas A. Matthews and Allan R. Sandage. Optical Identification of 3C 48, 3C 196, and 3C 286 with Stellar Objects. ApJ, 138:30, July 1963. Doi: 10.1086/147615.
- NRAO/AUI. Relativistic jet. URL https://astronomy.swin.edu.au/cosmos/g/Galactic+Jets. A radio image of the galaxy Cygnus A clearly shows the jet and radio lobes. The ‘hot spots’ that mark the shock fronts between the jet and the interstellar medium are clearly evident.
- Kathryn McKeough, Aneta Siemiginowska, C. C. Cheung, Lukasz Stawarz, Vinay L. Kashyap, Nathan Stein, Vasileios Stampoulis, David A. van Dyk, J. F. C. Wardle, N. P. Lee, D. E. Harris, D. A. Schwartz, Davide Donato, Laura Maraschi, and Fabrizio Tavecchio. DETECTING RELATIVISTIC x-RAY JETS IN HIGH-REDSHIFT QUASARS. The Astrophysical Journal, 833(1):123, dec 2016. doi: 10.3847/1538-4357/833/1/123. URL https://doi.org/10.3847%2F1538-4357%2F833%2F1%2F123.
- Antonella Fruscione, Jonathan C. McDowell, Glenn E. Allen, Nancy S. Brick-house, Douglas J. Burke, John E. Davis, Nick Durham, Martin Elvis, 27Elizabeth C. Galle, Daniel E. Harris, David P. Huenemoerder, John C. Houck, Bish Ishibashi, Margarita Karovska, Fabrizio Nicastro, Michael S. Noble, Michael A. Nowak, Frank A. Primini, Aneta Siemiginowska, Ran- dall K. Smith, and Michael Wise. CIAO: Chandra’s data analysis system. In David R. Silva and Rodger E. Doxsey, editors, Observatory Operations: Strategies, Processes, and Systems, volume 6270 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, page 62701V, June 2006. doi: 10.1117/12.671760.
- John E. Davis, Marshall W. Bautz, Daniel Dewey, Ralf K. Heilmann, John C. Houck, David P. Huenemoerder, Herman L. Marshall, Michael A. Nowak, Mark L. Schattenburg, Norbert S. Schulz, and Randall K. Smith. Raytracing with MARX: x-ray observatory design, calibration, and support. In Tadayuki Takahashi, Stephen S. Murray, and Jan-Willem A. den Herder, editors, Space Telescopes and Instrumentation 2012: Ultraviolet to Gamma Ray, volume 8443 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, page 84431A, September 2012. Doi: 10.1117/12.926937.
- Francis A. Primini, John C. Houck, John E. Davis, Michael A. Nowak, Ian N. Evans, Kenny J. Glotfelty, Craig S. Anderson, Nina R. Bonaventura, Judy C. Chen, Stephen M. Doe, Janet D. Evans, Giuseppina Fabbiano, Elizabeth C. Galle, Danny G. Gibbs, John D. Grier, Roger M. Hain, Diane M. Hall, Peter N. Harbo, Xiangqun Helen He, Margarita Karovska, Vinay L. Kashyap, Jennifer Lauer, Michael L. McCollough, Jonathan C. McDowell, Joseph B. Miller, Arik W. Mitschang, Douglas L. Morgan, Amy E. Mossman, Joy S. Nichols, David A. Plummer, Brian L. Refsdal, Arnold H. Rots, Aneta Siemiginowska, Beth A. Sundheim, Michael S. Tibbetts, David W. Van Stone, Sherry L. Winkelman, and Panagoula Zografou. Statistical Characterization of the Chandra Source Catalog. ApJS, 194(2):37, June 2011. doi: 10.1088/0067-0049/194/2/37.
- Nathan M. Stein, David A. van Dyk, Vinay L. Kashyap, and Aneta Siemiginowska. Detecting Unspecified Structure in Low-count Images. ApJ, 813 (1):66, November 2015. doi: 10.1088/0004-637X/813/1/66.
- David N. Esch, Alanna Connors, Margarita Karovska, and David A. van Dyk. An Image Restoration Technique with Error Estimates. ApJ, 610 (2):1213–1227, August 2004. doi: 10.1086/421761.
- K. Solipuram, M. Georganopoulos, and E. Meyer. X-Ray-to-Radio Offset Inference from Low-Count X-Ray Jets. In American Astronomical Society 28 Meeting Abstracts, volume 53 of American Astronomical Society Meeting Abstracts, page 209.05, January 2021.

Thank You