N O T I C E

X-ray Inverse Compton Emission from the Radio Halo of M87

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Final Technical Report

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Background and Summary

A significant fraction of known galaxies contain an 'active galactic nucleus' (AGN) at their cores, the site of violent activity and non-stellar radiation seen across the entire electromagnetic spectrum. This activity is thought to be due to the accretion of gas onto a massive black hole. A fraction of AGNs also eject collimated beams of energetic material, usually seen by virtue of its synchrotron emission in the radio band. Efforts to study these jets from AGNs in the X-ray band with the Einstein Observatory has led to several detections, most notably the jets in the nearby radio galaxies Centaurus A and Virgo A = M87. In their study of M87, Schreier, Gorenstein and Feigelson (1982) noted that, in addition to the synchrotron jet 10"-20" from the nucleus, X-rays appear to be generated in the diffuse 'radio halo' 2'-5' from the nucleus. This finding may be particularly important as it may constitute the first known case of X-ray inverse Compton emission from AGN ejecta, allowing for the first time direct determination of the magnetic field strengths.

The present study is intended to investigate in detail the associated X-ray and radio emission in the halo of M87. It involves analysis of the Einstein High Resolution Imager (HRI) data, and acquisition of improved radio maps of the halo with the NRAO Very Large Array. In the X-ray band, two deep HRI images were merged and the symmetric X-ray component from the dense interstellar medium in M87 was removed. In the radio band, VLA maps at 1.4 GHz were obtained with greatly improved resolution and dynamic range compared to previous maps. The comparison of the X-ray and radio structures proved surprising, as they are clearly related to each other yet are not entirely coincident as expected from a simple inverse Compton model. Either a more complex Compton model, involving variable magnetic fields with strengths an order of magnitude below equipartition, must be invoked, or an alternative thermal model, involving compression of the interstellar medium by the outflowing jet, is operative. The current data to not permit confident discrimination between these possibilities, though the thermal model may be more plausible. Critical tests involving future X-ray missions and optical narrow-band imagery are suggests.

History of the prcject

The X-ray analysis proceeded smoothly according to the plan proposed. The HRI data were reprocessed (Rev. 1.0) at the Harvard-Smithsonian Center for Astrophysics, and the merged image was tansported by FITS tape to Penn State, where models of the symmetric thermal emission were subtracted from it. The residual map was then placed in the NRAO AIPS (Astronomical Image Processing System) software environment for quantitative comparison with the radio data. This work was done mainly by Perry Wood, a graduate student of astronomy at Penn State, under the guidance of the PI. It was completed by the end of 1984 and was written up by Mr. Wood as his Master's thesis in early 1985.

Obtaining adequate radio data prove much more difficult. The VLA data acquired by us specifically for comparison with the HRI image proved useless after extensive computational efforts (equivalent to thousands of CPU hours on a VAX 11/780) were expended to extract a useful map. The problem is that the data was taken with the VLA in a moderate resolution configuration, but the Vir A halo is so diffuse that most of the emission was resolved out and not recoverable from the incompletely sampled Fourier UV plane. By mid-1984, all analysis techniques had proved fruitless and we sought lower resolution data obtained by other researchers. Two such data sets were kindly made available by Dr. R. Perley (NRAO-VLA) and Dr. M. Reid (Center for Astrophysics) which, after extensive reduction, gave successful radio maps. Most of the latter analysis was done on the new supermicro computer system in the Department of Astronomy at Penn State with the assistance of an undergraduate student Mr. M. Cline. Earlier efforts involved the VAXs at NRAO-VLA, NRAO-Charlottesville, and the Center for Astrophysics. The radio analysis was completed by mid-1985, following which scientific interpretation and paper writing proceeded. Submission of the principal paper for publication will occur in late 1985.

Results

The findings of the study are described in detail in the attached 'Results' document. It presents morphological and quantitative analyses of the X-ray and radio structures of the M87 halo, and discusses the inverse Compton, thermal, and other possible explanations for the X-ray emission. Appendices deal with two peripheral issues: an asymmetric X-ray component probably associated with an eccentricity in the gravitational potential of M87, and a discussion of the radio structure in terms of current models of radio galaxy physics.

Publications and Presentations

The principal publication will the the attached 'Results' document, which will be submitted after some revision to the Astrophysical Journal, Part I. The PI will be the first author, and co-authors may include P. Wood (Penn State), E. Schreier (Space Telescope Science Institute), D. Harris and M. Reid (Center for Astrophysics). The X-ray analysis is also described in Mr. Wood's unpublished Master's thesis. Preliminary results have been included in a review lecture on X-ray jets given by the PI at the Japan/U.S. Seminar on Compact Galactic and Extragalactic X-ray Sources (Tokyo, January 1985). The same talk was presented as a poster paper at the international conference Jets in Stars and Galaxies (Toronto, June 1985). The PI plans to present the final results as a contributed paper at the forthcoming American Astronomical Society meeting in June 1986.

The bibliography to date, copies of which are enclosed, is as follows:

Feigelson, Eric D. "Cosmic X-ray Jets", in Compact Galactic and Extragalactic X-ray Sources (Y. Tanaka and W. Lewin, eds.), p. 301.

Wood, P. A. D. "X-ray Inverse Compton Emission from the Radio Halo of M87", M.S. thesis, Penn State Univ.