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FINAL REPORT

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STUDIES OF X-RAY CLUSTERS OF GALAXIES/ INTERGALACTIC PLASMAS

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DATE:

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I. PURPOSE

The purpose of this NASA SRT grant was to study intergalactic plasmas from both an observational and a theoretical point of view. The observational work focussed on the development of a unique new spectroscopic technique designed to simultaneously obtain the spectra of 44 galaxies in a cluster of galaxies. This automated multi-object spectrometer, the "MX Spectrograph", now makes it possible to obtain detailed dynamical information on clusters of galaxies that can be compared with X-ray emission from hot gas in these clusters.

The theoretical portion of the grant involved the study of QSO winds and their effects on the interstellar and intergalactic environment.

The principal investigator, Dr. John S. Scott, left Steward Observatory and the astronomical community to accept a job in private industry during the course of this grant (August 1983). Dr. Scott chose to no longer be associated with this research or this research grant after his departure. Therefore, this final report has been prepared by Dr. John T. Stocke who has been associated with the grant only since Dr. Scott's departure.

Preprints and reprints supported by this grant are attached.

II. OBSERVATIONAL STUDIES OF CLUSTERS OF GALAXIES

Progress on observations of clusters of galaxies with the MX Spectrometer has been slow, but steady. The MX mobile fiber spectrometer is now in the construction phase, and should be operational by the winter (1984-85) observing season. Earlier observations of 250 galaxies with the Medusa aperture plate system and an intensified CCD detector are now in the reduction stages. Preliminary results are outlined in Section A below in excerpts from Dr. John Hill's Ph.D. dissertation (1984). A major activity since the departure of Dr. John Scott has been the development of an efficient data reduction system capable of handling the large amounts of spectroscopic data produced by multiple fiber spectrometers. The system we have developed is described in another section of Dr. Hill's dissertation (see Section B below). NASA funds have been used to pay student programmers and to purchase a pair of removable disk packs for the VICOM image processor with which the multi-object spectra will be reduced.

A. Observations with the Medusa Spectrograph

Figure 3 shows a set of galaxy spectra from a 3 hour exposure on A576 taken in December 1980. The dispersion was 250 Å mm^{-1} from a 300 l mm^{-1} grating with a resolution of 12Å. Velocities were measured from this N_2 baked IIIaJ photographic plate and several others to an accuracy of 90 km s^{-1} by Hintzen, et al. (1982). The

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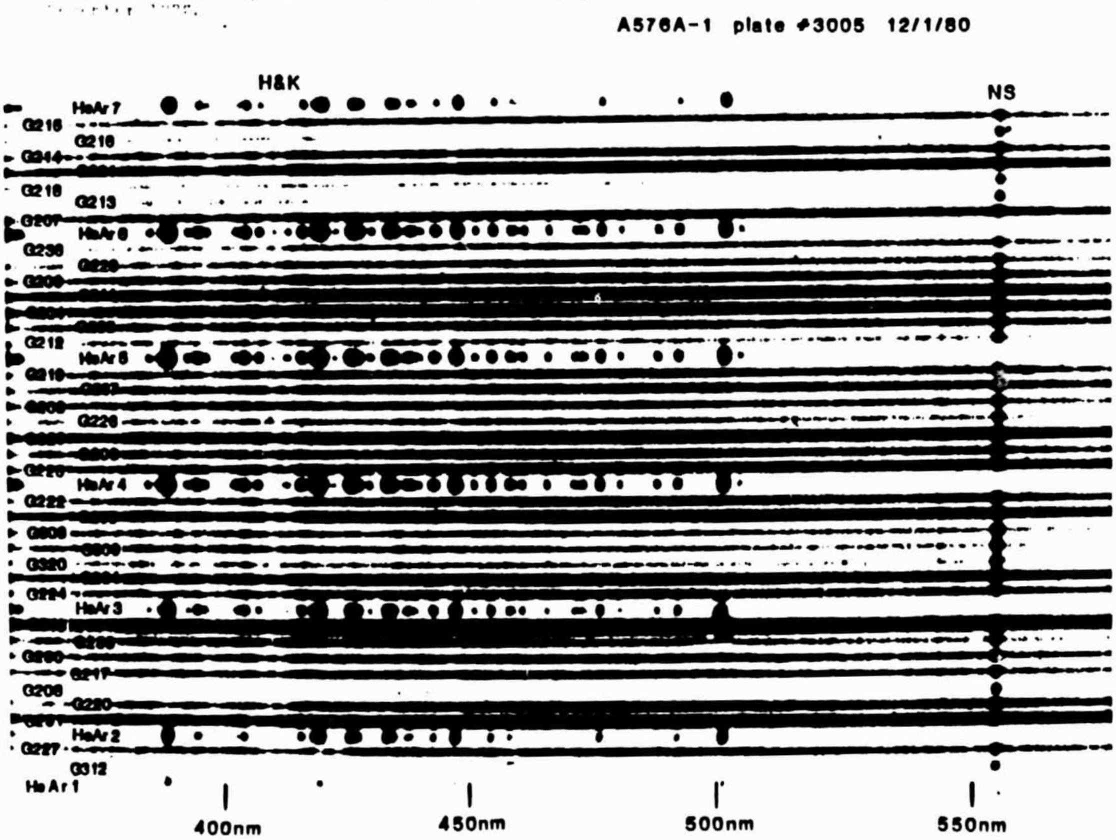

Figure 3. Photograph of 37 Spectra from A576

This figure shows intensified photographic spectra of 37 objects in the cluster of galaxies Abell 576. A three hour exposure at the 2.3m telescope, December 1980. The spectra are identified by galaxy number and blue is to the left.

wavelength scale is labelled on the spectra along with galaxy ID numbers. The position of the redshifted calcium H and K lines is also indicated. The heliocentric redshift of A576 is 0.0381 ±0.0005. The global radial velocity dispersion derived from measurements of 47 galaxies in A576 was found to be 914 (+113, -83) km s^{-1}. Since the cluster gas density varies with the square of the velocity dispersion, our observations imply that the gas density is only 2/3 the value adopted by White and Silk (1980). This strengthened their conclusions from X-ray data, that there was too little hot gas to account for the observed microwave decrement. More recent microwave observations at 6 cm by Lasenby and Davies (1982) have failed to show any significant microwave decrement in A576. Rothenflug, et al. (1983) report Solid State Spectrometer observations showing in the center of the cluster a lower X-ray temperature which is consistent with the observed galaxy velocities. They suggest that the lower X-ray temperature may be due to a cooling flow in the X-ray gas or to the emission of individual cluster galaxies. Neither X-ray nor optical data are able to distinguish between these two modes. Birkinshaw and Gull (1984) describe the state of recent microwave decrement observations in serveral cluster.

The results above assume that both the gas and the galaxies are in equilibrium, and that their distributions reflect the same symmetric potential. Our sample of velocities in A576 provides no evidence for large-scale cluster rotation. Therefore, the line-of-sight velocity dispersion is a good measure of the gravitational potential of the system. The radial velocity dispersion shows only a slow decrease with increasing radius from the cluster center. This seems to confirm the conclusion, which White and Silk draw from X-ray observations, that the binding mass of the cluster is distributed over a region significatly larger than the "cluster core". Additional studies are underway to provide more data on the velocity structure of the galaxies in A576.

The Medusa spectrograph has collected about 800 spectra of galaxies as of Febreary, 1983. The major portion of these (200 redshifts) will be published by Hill, et al. (1984). Figure 4 shows plots of raw spectra of five galaxies in the cluster Abell 2151 obtained with the intensified CCD detector at the 2.3m telescope. This single 20-minute exposure includes galaxies with visual magnitudes from 15.0 to 17.5. Additional exposures were taken to measure the redshifts of the fainter galaxies. The spectral resolution is 12 Å FWHM. The CCD allows more sophisticated data reduction including subtraction of the sky background obtained with fibers looking at empty areas of the field. Except for flexure, the fixed format of the CCD allows direct velocity calibration of each fiber by taking full-field comparison lamp exposures. This added complexity also requires more time spent at the computer to obtain a radial velocity.

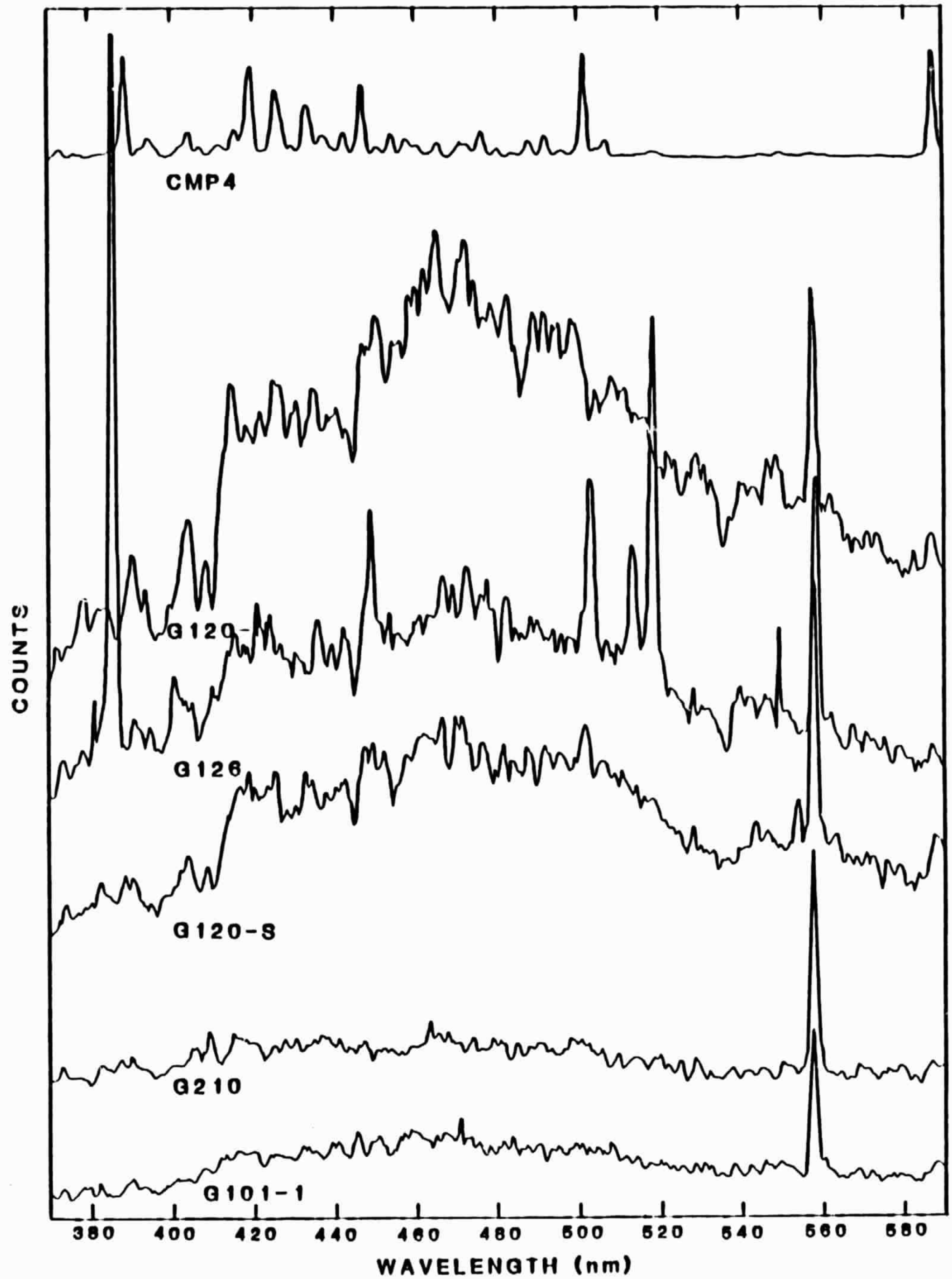

Figure 4. Plots of CCD Spectra from Abell 2151.

This figure shows raw Medusa spectra of galaxies in the cluster Abell 2151 (Hercules) were taken on 14 June 82 at the Steward 2.3m telescope (exp A2151-1.G6). These spectra are 5 of 37 which were extracted from a single 20-minute intensified CCD exposure. All galaxy spectra are plotted on the same scale with a vertical offset added.

B. Data Reduction

A series of programs and CLIs (macros) designated MARS = Multi Aperture Reduction System have been written by J. Eisenhamer, D. Silva, and M. Wenz, under the guidance of J. Hill with occasional assistance by A. Koski. The major features of MARS not seen in other spectral reduction systems include: a program that locates the indivudual spectra on a CCD frame and extracts them into a one-dimensional format, and a program that automatically fits dispersion curves to a series of similar HeAr spectra when supplied with an initial guess at the dispersion curve and a catalog of measurable lines. The MARS driver routines and all 1-D spectra manipulations run on the Data General Eclipse (S-250) computer under AOS. The two-dimensional data manipulations such as flat fields, frame alignment and defect removal are presently being implemented on a VICOM image processing system recently purchased by Steward Observatory. The VICOM can perform pipeline arithmetic and lookup table operations at 8 MHz pixel rates to process an entire image in one video frame time. A simple array processor can be used to operate at video rates on an image with a 3 x 3 small generating kernel.

After collection of the spectral and calibration CCD frames described in Table 2, each frame must be corrected for the flat field response and bias of the CCD detector. These operations will be done on the VICOM image processing system after we have modified it to retain 16 bit data for all operations. Because it was designed for visual image processing, the standard mode of VICOM operation uses 12 bit planes of memory for the image and 4 bit planes for eight-color graphics. Eleven bit signed integers (±4K) are fine for picture processing but are not adequate for astronomical data reduction involving multiple frame spectral images. Present Medusa data requires alignment of individual CCD exposures to remove flexure in the detector chain before further processing can occur. Individual frames are shifted by integer and fractional pixel amounts with the pipeline processor, so that the interlaced HeAr spectra between the galaxy spectra all coincide. Fractional pixel shifts in two dimensions can be performed by operation on the images with a 3 x 3 small generating kernel (SGK). The kernel performs bilinear interpolation of the pixels onto a displaced grid. Larger kernels could be used for more complicated interpolation schemes, but the linear term preserves most of the infomation in the sampled spectral image, while minimizing the blurring which occurs. We have not yet approached the problem of cosmic ray removal in a serious fashion, but it will ultimately be necessary to remove them from the data at this stage of the reduction processing.

After the indivudual frames have been refined and aligned, they are coadded to form the final spectral and calibration lamp images. To locate the individual spectra on the CCD frame, a copy of the coaddition result is filtered on the VICOM with a 5 x 5 kernel to smooth the data on pixel to pixel scales and to enhance features with the characteristic size of the spectra. This smooth frame is then searched for local maxima at the interfiber spacing to identify the individual spectra. Ten cuts are made transverse to the dispersion direction and a parabolic fit is used to locate the maximum position of each spectrum across the chip. These data points are then used to generate second-order polynomials which describe the locations of the spectra on the image frame. This set of polynomials is used as a map to direct the program which extracts the individual spectra from the original, not smoothed, data frames into one-dimensional files. Other parameters for the extraction process such as the width of spectrum to extract are entered by the user.

The one-dimensional files can be formatted to work on either of the spectral reduction systems now in use at Steward: IRS by C. Foltz, or CZWT by W. Tifft. In order to avoid the tedium of measuring the positions of thousands of helium and argon lines by hand, we have written an automatic routine to find dispersion curves for all of the comparison spectra on a given calibration frame. The program uses a rough dispersion curve of the first fiber spectrum on a frame to predict line positions on the next spectrum. The process continues across the entire length of the slit. With an accurate prediction, the program is able to find the center of the emission lines by fitting a parabola to the local maxima in the spectra. This program has been quite successful and usually produces a better dispersion curve than manual measurement while taking only 5% of the time previously required. I should point out that this routine is fast and efficient but not magic. If the calibration frame is of poor quality it will produce meaningless dispersion curves. Care must be taken to be sure that the data and the wavelength catalog are similar enough to prevent the prediction algorithm from becoming unstable.

Measurement of lines in galaxy spectra is currently done manually with IRS. Figure 21 shows one of 30 spectra extracted from a series of exposures in Abell 993B. Both the raw sum and the sky-subtracted sum of nine 20-minute exposures are shown. The raw extraction of a single 20-minute exposure is also shown. No flat field correction has been applied in this preliminary reduction. Large cosmic ray events were removed manually. The redshift measured from six absorption lines in galaxy 225 is 11720 km s^{-1}. At some time in the future we expect to use a cross correlation routine to automate the galaxy measurement process. When combined with manual verification, the cross correlation procedure should be faster and more reliable than manually measuring line positions. The major problems are expected to be creating templates, and removing cosmic rays and emission lines which would give false correlation peaks.

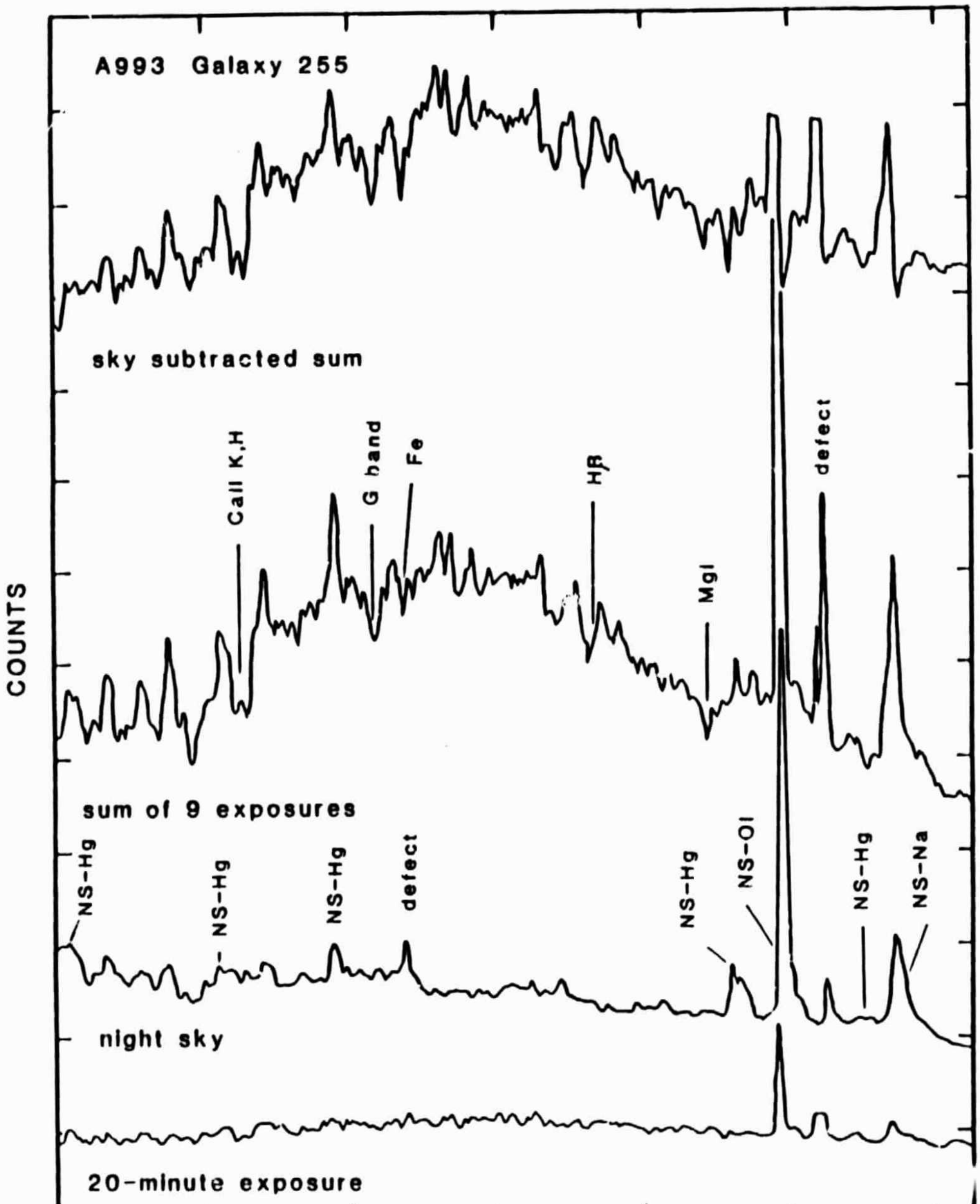

Figure 21. Spectrum of A993B.2.G255

This figure shows the spectrum of galaxy 255 in the cluster A993. The Medusa spectrograph with an intensified CCD detector was used on the 2.3m telescope. A single 20-minute exposure is plotted at the same scale as the raw and sky-subtracted sum of nine 20-minute frames. The spectral resolution is 12 Å.

III. THEORETICAL STUDIES OF QSO WINDS

In order to test the existence of "quasar-winds" (Weymann et al. 1982) in active galaxies and QSOs, the interaction between such a wind and the interstellar medium (ISM) has been investigated by A. V. R. Schiano as part of his doctoral dissertation (A. V. R. Schiano 1984a and b). This study concentrates on Seyfert galaxies since some effects of this interaction may be directly observable in nearby objects. In particular, certain properties of the Narrow Emission Line Regions (NELRs) of Seyfert galaxies may be due to the interaction of the ISM with such a wind.

Since Seyfert galaxies are predominantly spiral galaxies, the propagation of the wind into a flattened disk distribution of gas was investigated. The model interstellar medium environment (density, temperature, pressure, cloud sizes, etc.) was based on observed properties of the Milky Way and nearby spiral galaxies. Given the low number density of clouds in the ISM it is possible to separate the wind-gas and wind-cloud interactions based on cloud density alone (Sgro 1975). At low mechanical wind luminosity ($\log L\{wind\} \leq \log L\{photon\} = 42$ to 44 cgs) the wind fails to propagate to large enough distances in the galactic disk, and hence does not encounter enough clouds to require a more complicated analysis of the difference between gas and clouds in the model. However, at higher $L\{wind\}$ (appropriate for QSOs) the wind-cloud effects dominate the propagation of the wind.

The Kompaneets approximation (Kompaneets 1959) along with the stellar wind similarity solutions of Weaver et al. 1975 were used to investigate the propagation of the wind "bubble" in a flattened disk geometry. Since the bubble travels fastest in the lowest density gas, the bubble progresses rapidly along the galactic pole with a timescale of a few million years. In the disk the higher ISM gas density and pressure tends to slow the bubble's motion and eventually stops the wind near a point where the wind ram pressure equals the ISM gas pressure. This occurs at about 5 - 10 million years after wind turn-on. The stability of the solution is studied as well as the nature of the steady-state solution. The maximum distance that the wind reaches in the plane is of order 5 to 10 Kpc for log $L\{wind\}$ = 44 cgs. The observational effects of the wind-gas interaction are determined and found to be probably unobservable at present.

The interaction between the wind and interstellar clouds was also investigated. Due to the high ram pressure of the wind, interstellar clouds would be compressed to much higher than normal pressures and densities. Combining this with the effects of the photons from the active nucleus produces clouds with properties not unlike NELR clouds. The wind ram pressure is capable of accelerating large clouds (> 100 solar masses) to velocities comparable to those seen in NELR line profiles. It is also shown that under the conditions inferred for the regions between NELR clouds (log Temperature = 8 to 9 cgs), significant thermal evaporation of clouds occurs. Thus only large clouds can survive for a NELR crossing time. Such large clouds are incapable of being accelerated to high velocities (1000 kms) by photons alone. It is thus proposed that NELR clouds are normal interstellar clouds being accelerated and confined by a powerful quasar wind. Because of the relatively large size (1 to 10 Kpc) of the wind's extent, it may be possible to directly observe the wind in nearby, bright, Seyfert galaxies and hence prove or disprove the existence of the wind itself.

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