2.1 IUE

The IUE Project

The International Ultraviolet Explorer (IUE) satellite was launched into geosynchronous orbit on 26 January 1978 from Cape Canaveral Air Force Station; orbital operations were terminated on 30 September 1996. IUE was a joint project between NASA, ESA and the UK Particle Physics & Astronomy Research Council (PPARC). It was in continuous use for 18.5 years as an astronomical observatory in the 115-320 nm ultraviolet domain. Over these years of operations, the IUE Project has collected 104 552 spectral images, resulting in 109 945 spectra of some 10 000 different astronomical objects, extending from Earth-approaching comets to quasars at redshifts out to z = 2.6.

On 30 September 1996, the spacecraft was decommissioned by the deactivation of the radio frequency transmitters at 18:44 UT. Before turning off the spacecraft, several measures were taken to prevent the creation of orbital debris: the hydrazine tanks were completely vented and the batteries were discharged. No spacecraft re-orbiting was attempted as analysis showed that only minor adjustments were feasible, and the potential for IUE breakup was non-negligible. The spacecraft was tumbling at the time and it will, every 50 years, experience two periods of traversing the geostationary belt some 70 times in 3 months. The first of these crossings will occur in 1999 and 2001.

A final report on the long-term behaviour of the spacecraft and subsystems was published as ESA SP-1215. To mark the end of the IUE Project, the highly successful *UV Astrophysics Beyond the IUE Final Archive* conference was held in Sevilla, Spain in November 1996. The proceedings, reviewing the progress of UV astrophysics after 18.5 years of IUE observations, together with a forward look at new problems to be addressed in the ultraviolet range, was published as ESA SP-413.

Science operations and spacecraft

During its last year of operations, IUE was run in a ‘hybrid’ mode, which used minimal operational support from NASA. This revised operations mode, ‘HYBRID’ IUE Science Operations, consisted of the following:

— *Observing time and science operations* The 24 h of science operations were reduced to 16 h, corresponding to the low-radiation part of the orbit. All science operations were performed from the ESA IUE Observatory at Villafranca, Spain. For the remaining 8 h when the spacecraft was around perigee (i.e. when science capabilities were severely limited by the particle radiation background), only spacecraft control and housekeeping was supplied from NASA Goddard Space Flight Center.

— *Time allocation* A Joint (ESA, NASA, PPARC) IUE Allocation Committee was formed to evaluate, for the first time jointly by the three agencies, the worldwide applications for IUE observing time.

— *Time distribution* The ESA IUE Observatory made a commitment to perform the approved observations, taking into consideration only the spacecraft constraints, while optimising the scientific return.

— *Observer presence* All science observations were made in service mode.

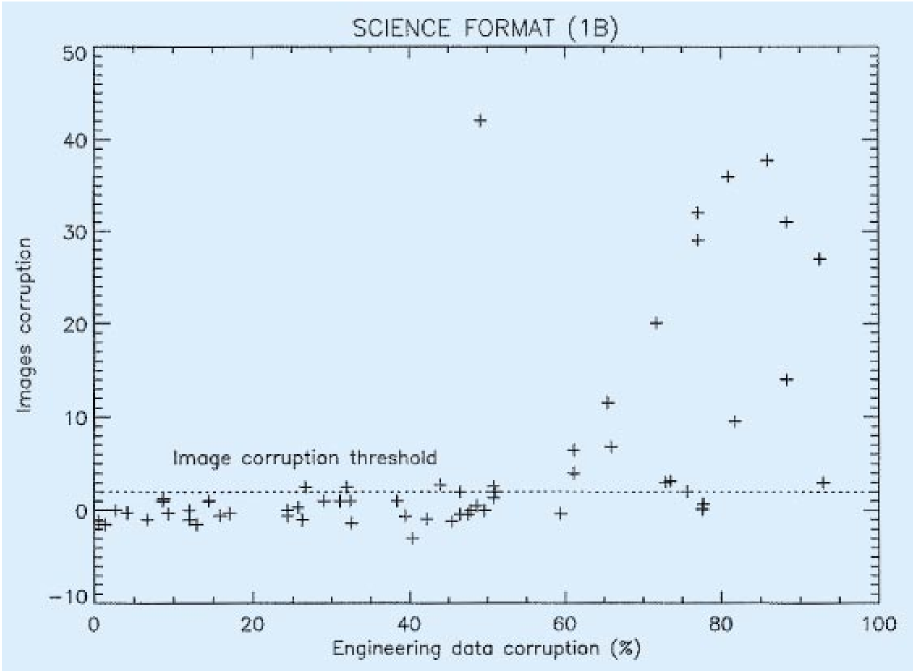
— *Proprietary rights* The proprietary rights of 6 months for the observations made under hybrid operations were waived by all applicants.

— *Data delivery* All reduced data were available on-line to the whole science community within 48 h of the processing of the image.

As was to be expected, the spacecraft continued to show signs of further degradation.

Further information on the IUE Project can be found at http://www.vilspa.esa.es/iue/iue.html

Figure 2.1.1. This figure illustrates the evolution of the 159 DMU anomaly that developed aboard IUE over the last 2 years as a consequence of radiation damage to the Data Multiplexer Unit. In the early stages, the occurrence frequency was such that it could be seen only in non-critical engineering data. However, as the frequency increased and the engineering data corruption exceeded about 70%, the science data were also clearly affected.



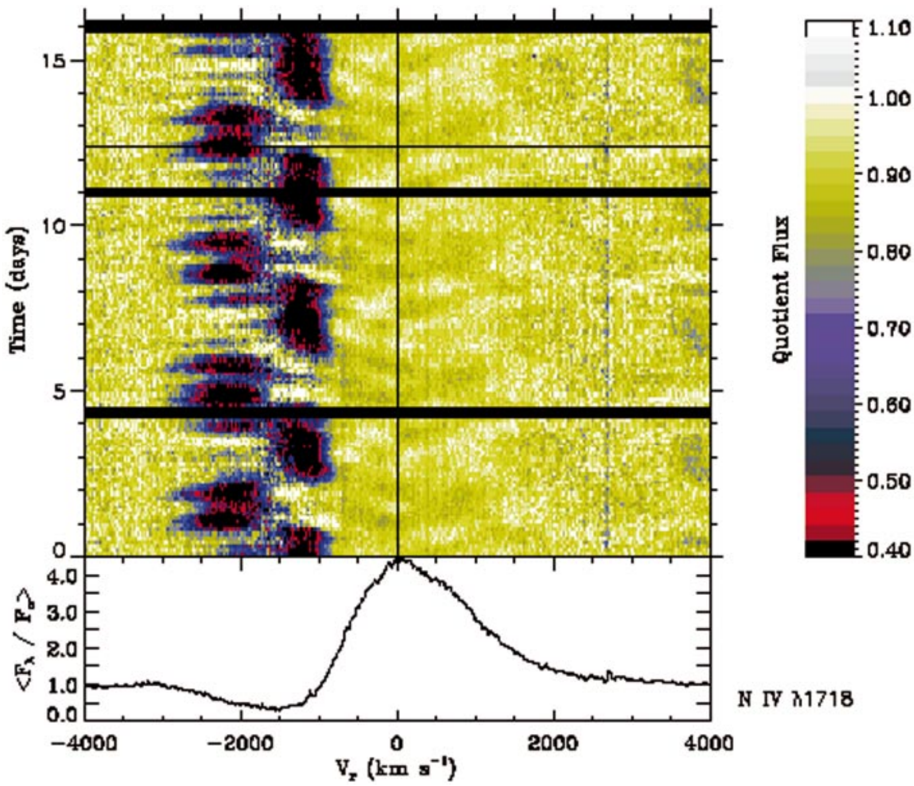


Figure 2.1.2. The variability in the wind structure in the WN5 star HD 50896 (EZ CMA) over 16 consecutive days of observations as seen in the unsaturated subordinate NIV 171.8 nm line. In this figure, time increases upwards and the individual spectra are placed on a linear timegrid by a nearest neighbour interpolation scheme. The dark horizontal lines indicate gaps in the data. The spectra have been normalised through division by a maximum flux (minimum absorption) spectrum. Such normalisation has the desirable property that it makes all changes appear as absorptions. Note the very stable wind structure, which repeats with the orbital period of 3.76 d.

159 Anomaly
A new problem was identified as radiation damage to the Data Multiplexer Unit (DMU). In its early stages, this affected only non-essential engineering data, but with time it also started to corrupt the science data (see Figure 2.1.1). It meant that all image pixels with values between 160 and 191 were registered as 159.

Fifth Gyro Failure
The second major spacecraft problem occurred on 6 March 1996, when a ground command mix-up switched off Gyro #5. As the gyro could not be restarted, the spacecraft was left with only one operational gyroscope. The loading of an experimental 1-gyro control system was successfully accomplished and within a month the science programme resumed with a 3-axis stabilised spacecraft.

As a consequence of the 1-gyro control system, some new restrictions had to be imposed on the science programme, because only targets with a bright guide star in the Fine Error Sensor (FES) field of view could be held in the spectrograph apertures for long exposures.

Final IUE Science Programme
During the last 2 years of operations, a special joint NASA/ESA/PPARC science programme was selected to ensure that IUE's 19th observational period paid special attention to those scientific questions, raised by the previous 18.5 years of observations, that could be addressed only by the specific capabilities of the IUE Project (e.g. stable instrumental configuration over 18.5 years, extended continuous viewing of sources, and large wavelength coverage in single exposures).

Although the Final Programme had to be modified as a consequence of the fifth gyro failure in March 1996, a redefinition of the targets still achieved 90% of the defined Lasting Value Programmes in the 1-gyro mode. This programme included major campaigns such as:

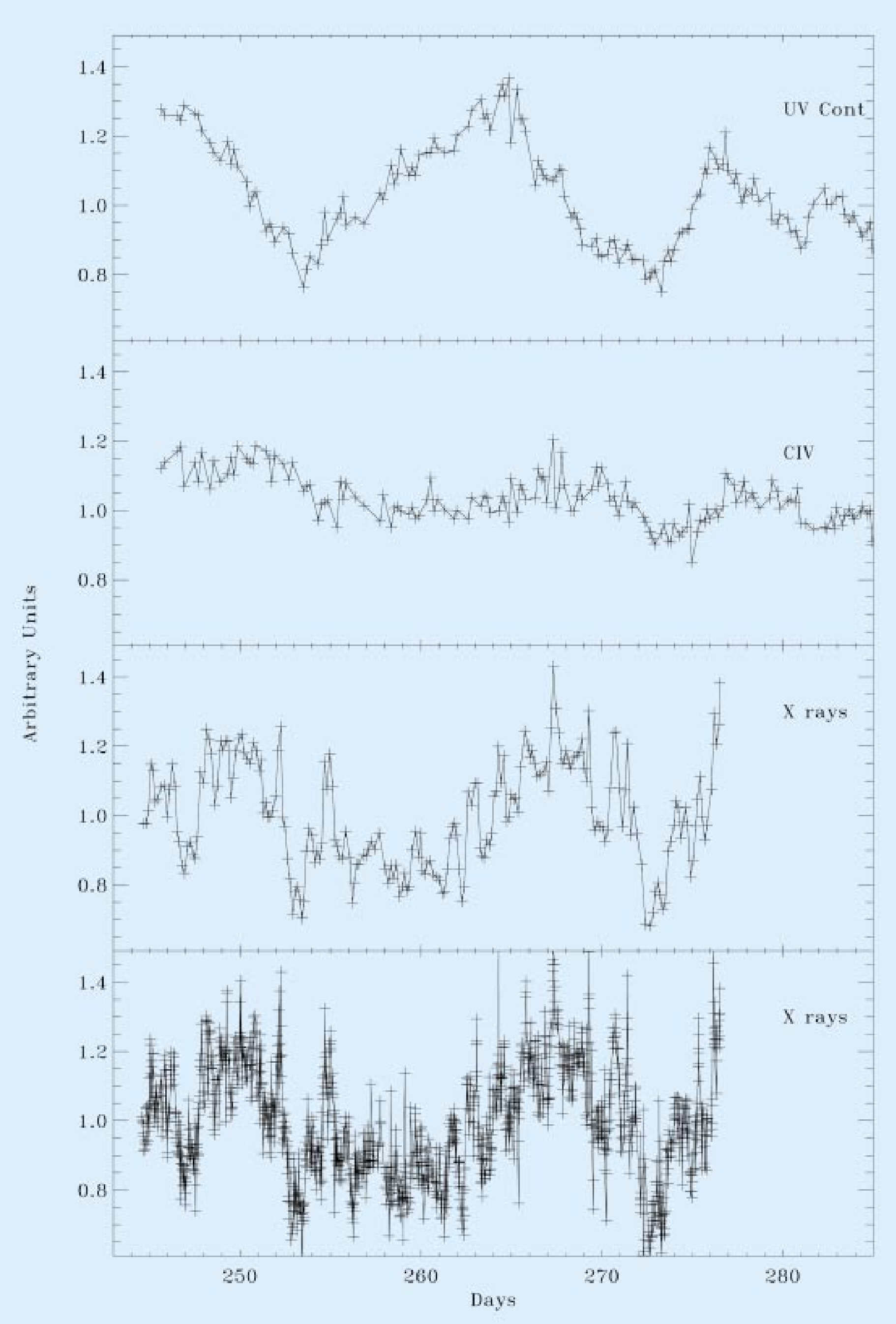
— A complete remapping (40 days) of the jovian system (Galilean satellites, Io Torus, jovian atmosphere and aurora) in coordination with Galileo and Hubble Space Telescope (HST). This also allowed a revisit to the Jupiter atmosphere to evaluate the persistence of effects of the Shoemaker-Levy-9 cometary impact after 2 years (International Jupiter Watch).
— Target of Opportunity Programmes on the close Comet Hyakutake and an important series of pre-perihelion observations of Comet Hale-Bopp.
— Short-term wind instabilities (19 days) in OB stars and Wolf-Rayet stars (see Figure 2.1.2).
— Maximum time density sampling (35 days) of the variations in the Seyfert I galaxy NGC 7469 (see Figure 2.1.3) in coordination with RXTE, HST and ground-based observations (International AGN Watch).
— Continuous multi-frequency mapping of a BL Lac object in coordination with RXTE, HST and other ground-based observatories (20 days).

The IUE Archives

The IUE Data Archive remains the most heavily-used archive in astronomy. With a total of 550 000 data sets delivered in archival form, together with delivery to the Principal Investigators, the IUE data have already been used at least six times over by the scientific community. As the archive has always been an important part of the Project, it was decided to ensure its optimum usefulness after termination of orbital operations by reprocessing all the data with a new spectroscopic reduction software: NEWSIPS (New Spectral Image Processing System). This was performed in the last

Figure 2.1.3. The lightcurves of the last of the series of multi-wavelength reverberation experiments by the AGN Watch consortium. This represented the most complete reverberation experiment ever performed. The Seyfert I galaxy NGC 7469 was monitored continuously for 41 d with IUE and simultaneously for 33 d with RXTE, while ground-based spectra were obtained at the same time. This is the first time that it has been possible to monitor the variations of an AGN in the UV without undersampling. The figure shows from top to bottom: the UV continuum at 135 nm; the strength of the CIV line at 154.9 nm; the X-ray lightcurve observed by RXTE with the same sampling as in the UV; the X-ray data at the original time resolution.

These results show, for the first time, a clear difference between the X-ray lightcurve and that of the UV continuum. Although the variations in CIV are rather small, it appears that the CIV lightcurve in these observations is better correlated with X-rays than with the UV continuum, contrary to the behaviour of most other AGN studied in earlier reverberation experiments.



2 years of the project. This brought all the data to a homogeneous format and reduction so that the 109 945 extracted spectra can be used directly for scientific studies without reference to the history of the data processing and spacecraft behaviour.

It has long been clear that easy access to the data was an important factor in its use, as was well illustrated by the heavy usage of ESA's Uniform Low Dispersion Archive

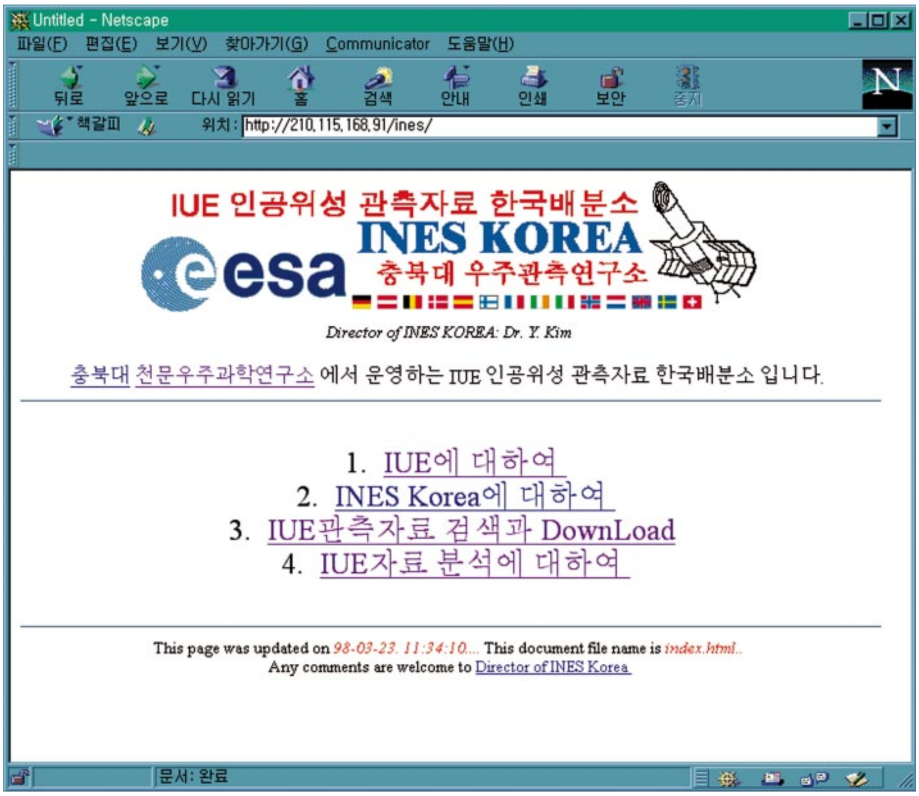


Figure 2.1.4. The homepage of the INES (IUE Newly Extracted Spectra) National Host installation at the Chungbuk National University in Cheong-Ju, South Korea. These mirror sites for query and retrieval access to the data in the IUE Final Archive will greatly facilitate access by the worldwide community to space data, such as that available in the 110 000 UV spectra obtained over the years with IUE. Although the system structure and data are supplied by the ESA IUE Observatory, and will be the same all over the world, the user interface has been adjusted to local requirements. This approach greatly contributed to the early heavy use of ULDA and will do the same for INES data. The larger data sets will be completely transparently to users, served from the INES Principal Center.

(ULDA) access scheme, which was based on a distributed archive structure around National Hosts serving their local communities. Therefore, a special effort has been made by ESA to maintain this structure and to bring it up to date through new distribution software, INES (IUE Newly Extracted Spectra), based on the WWW using the National Hosts as INES mirror sites (Figure 2.1.4). The INES system is being implemented in the National Host institutes and will allow fully independent data transfer by and to the users in a modern computing and communications environment.

It became clear during the reprocessing for the IUE Final Archive, through the science verification effort performed in parallel with the processing, that some problems were still present in the NEWSIPS extraction method. A new extraction scheme has therefore been applied in the preparation of INES, together with some additional improvements which significantly enhance the reliability and applicability of the spectra. Also, full concatenation of the high-resolution data has been done in the INES production. It is expected that, after all the INES Host installations (currently in 30 countries and likely to increase) have been completed, the full archival structure, including the Principal Centre functionality, will become part of the astronomical community, with no further obligations from the Agencies. The INES dataserver for the IUE Archive is operational at http://ines.vilspa.esa.es/ines/

Scientific highlights

Solar System

The final year of IUE observations saw considerable activity focusing on comets, with the unique opportunities provided by the early discovery of Comet Hale-Bopp

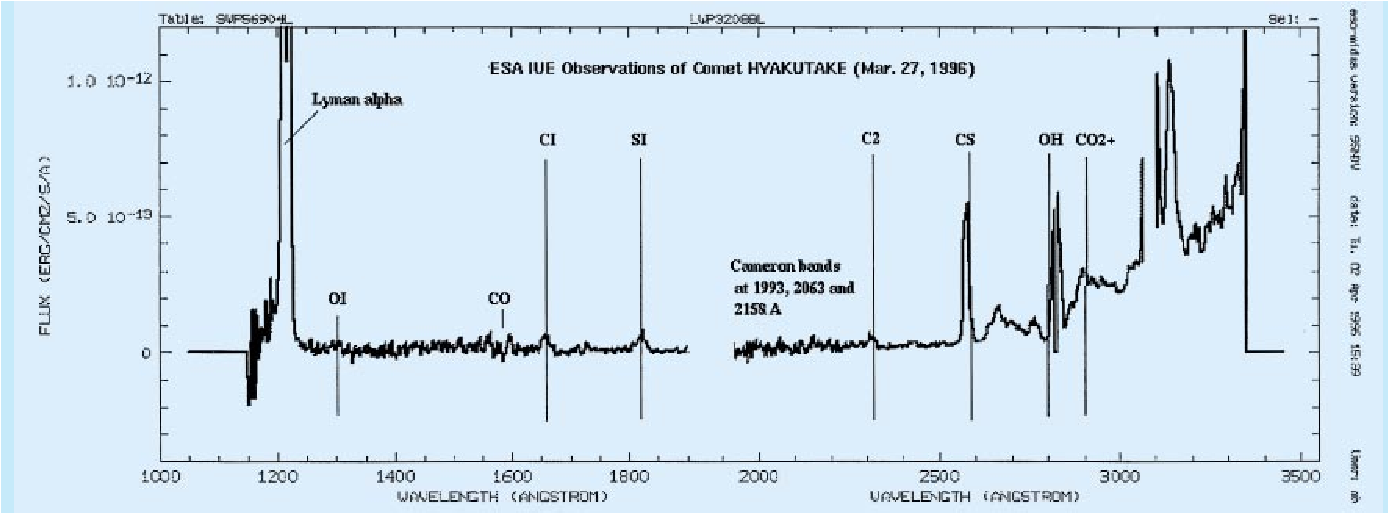


Figure 2.1.5. The combined spectrum in the long and short wavelength range of Comet Hyakutake. The comet's brightness made it possible to determine the evaporation rates of the major nucleus constituents. Simultaneously determining the H_2O, CO and CO_2 rates provided important information on the structure and composition of the nucleus.

and the very close Earth passage of Comet Hyakutake. The observations of Hale-Bopp were of great interest because they studied the onset of water sublimation. The spectra taken at different epochs allow a very detailed study of the onset of the H_2O evaporation process as it takes over from CO and thus controls the temperature of the nucleus. This is the first time that this phenomenon has been monitored at non-radio wavelengths, and suggests that water can sublimate at much larger heliocentric distances than was previously thought. This is likely due to sublimation near the subsolar point and suggests that the temperature in that region is higher than expected. In the 8 months before May 1996, the H_2O production rate increased by a factor of 15, far surpassing anything ever seen before at that solar distance.

The difficult observations of Comet Hyakutake (cometary motion reached 1°/h and IUE's new 1-gyro control system), have allowed the simultaneous determination of the H_2O, CO and CO_2 production rates at the nucleus (see Figure 2.1.5). The H_2O rate showed a significant short duration increase during the break-up event, suggesting that the comet lost only small pieces and did not really break up. The difference between the nuclear CO production rate found in the UV and that derived from the sub-mm observations suggests that most of the CO in the coma originates from a distributed source, in a similar way to Comet Halley.

The last observations of the jovian aurorae found completely unexpected short-term (h) and quite large (up to a factor of 2) variations in the strength. These will be important for comparisons with other related magnetospheric and solar wind interactions.

Stars

Observations of Blue-Horizontal-Branch stars in M4 and NGC 6752 suggest that all these stars have evolved off the Zero-Age-Horizontal-Branch, consistent with theoretical predictions. The previously suggested presence of low-gravity stars in M4 has been confirmed, while no evidence was found for multiple populations in NGC 6752. Various extensive studies on the nature of the variability of stellar winds in early-type stars have shown that, for example, in the star Zeta Puppis acceleration mechanisms in the wind flow are possibly associated with a periodicity of some 19 h, as well as with a rotation period in the late-type companion of 5.2 days. Alternatively, the wind variations in the Wolf Rayet star EZ CMA were found to be clearly locked into the 3.766 d period. This suggests a global wind structure pattern that remains quite stable in the frame of the star and can best be explained by some co-rotating interaction regions emanating from hot (magnetically?) active regions near the surface of the stellar core. Even though somewhat ad hoc, such a model better accounts for the observed detailed structures than does the alternative model involving an ionisation cavity around an accreting neutron star companion.

A phase-resolved study of the newly discovered magnetic cataclysmic variable RE1938-461 associated with the orbital period of 2.3 h has allowed the different variability mechanisms to be untangled. The emission lines of HeII, CV and NV were all found to be highly variable in both intensity and velocity. The changes observed in the equivalent width of the lines strongly suggests that the lines are not formed in the same regions as the continuum. They are most likely associated with the reprocessing of the soft X-rays emitted at the magnetic pole of the white dwarf.

Extragalactic Studies

Analysis of the brightness variations of 3C390.3 has shown that, in this Broad Line Radio Galaxy, optically thin and thick BLR clouds coexist within a radius of 95 light-days. This is the first time that any difference in behaviour has been found for a radio-loud object when compared with the radio-quiet AGN studied in detail. These last objects all tend to show only evidence for the presence of optically thick clouds. The mass of the central object in 3C390.3 is confined within the range of $1.5\text{-}4.5 \cdot 10^8$ M_{Sun}. This AGN shows that the Radius-Luminosity relation predicted for active galaxies does not seem to hold up for all objects. As similar results were found from the intensive monitoring campaign with IUE on the high-luminosity Seyfert I galaxy Fairall-9, these results seem to suggest that this relation is not a firm property of all AGN.

The extensive multi-wavelength studies of blazars have shown that a unified continuum can be applied to this class of objects. This suggests that the same basic mechanisms are active in these objects: synchrotron and inverse Compton radiation. The differences found for different objects and at different times would then be the consequence of variations in the local conditions, such as magnetic field strength, critical particle energy, and the relative importance of the contribution of ambient photons *vs* synchrotron radiation for the inverse Compton process.

A major reverberation study has been made of the Seyfert I galaxy NGC 7469 in the Final IUE Programme. The results show for the first time variation in the spectral index of the continuum with brightness, indicating that the disc radiation in this object might not be varying with a constant spectral index, as was found for all the objects studied previously. The high-density sampling (interval some 3 h) of this object has shown that the full frequency domain of the UV continuum variations was sampled. On the other hand, the simultaneous X-ray observations showed clear evidence for higher frequency variability (see also Figure 2.1.3).