NEW INSIGHT INTO THE PHYSICAL STATE OF GALAXIES AND QUASARS

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Data from the International Ultraviolet Explorer satellite have revolutionized many concepts in extragalactic astronomy. These include the physical processes at work in the emitting gas characteristic of active objects, the nature of the continuum source itself in those objects, and the constituent hot stellar and gaseous components of normal galaxies. This review will not be exhaustive, but will concentrate on several problems of extragalactic research investigated with IUE.

NORMAL GALAXIES

The spectral energy distributions of normal galaxies contain information valuable for two related problems: population synthesis, for which optical spectra alone are not sufficient to deduce the parameters relevant to hot stars; and studies of high-redshift galaxies to determine both cosmological constants and galactic evolution.

Several of these difficult observations have been made with IUE, including the nuclei of M81 and M87 (ref. 1), M31 and M32 (ref. 2, 3), NGC 4472 (ref. 3), NGC 3379 (ref. 4), and NGC 1052 (ref. 5). The calibrated spectrophotometry from IUE shows good agreement with that of ANS, in particular for M31 and M81 (ref. 6), and in general for a large body of ANS galaxy observations (ref. 7).

All authors agree that the observations cannot be explained by a simple extension below 2500 Å of the spectrum representative of a pure old metal-rich population dominated by G and K stars. Simple spectral fitting suggests the presence of a population of type A0 for M81 (ref. 1) to early F for NGC 1052 (ref. 5). More sophisticated modeling for the bulge of M31 (ref. 3, 6) admits several possibilities. An acceptable fit is obtained from an old Population I (M67) cluster horizontal branch plus blue stragglers. Much better fits are derived for both long and short ultraviolet wavelengths from Population II, globular cluster horizontal branches. These stars would contribute 5 to 10% of the light in the V band and 75% of the light at 2000 Å. Several lines of evidence suggest that the UV light does not represent OB associations. It will be important to assess the contribution of hot stars between the red giant and white dwarf phases, such as planetary nebula nuclei, sdO and sdB stars. An important implication of these results is the large range in metallicity for elliptical systems, both in the presence of metal-poor stars and in the requirement of a metal-enhanced population to offset the dilution in optical absorption line strength produced by the redder Population II stars that must co-exist with the horizontal branch.

Ultraviolet observations of low-redshift galaxies may be used for comparison with optical observations of high-redshift galaxies. The two absorption breaks used for redshift determination, one primarily from MgII at 2800 Å and one primarily from FeII at 2640 Å, are both detected at their expected strengths (refs. 2, 3). In general, galaxies observed through fixed bandpasses will reach, as a function of increasing redshift, a maximum redward excursion in color, then become bluer again at higher redshifts. For spirals, this turning point is reached at $Z \sim 0.7$ in V-R, while for ellipticals it is found at $Z \sim 1.2$ (ref. 7). Since spirals have more ultraviolet flux relative to visual than ellipticals, beyond some redshift brightest cluster galaxies observed through a fixed bandpass will be giant spirals rather than giant ellipticals. The above predictions may now be compared with observations of high-redshift galaxies to learn about population evolution.

A significant result of IUE has been the discovery of a highly ionized halo around the Galaxy (refs. 8, 9) and around the Large and Small Magellanic Clouds (refs. 8, 10). C IV and Si IV have been detected in absorption with strengths implying column densities around 10^{14} cm^{-2} (refs. 8, 11). If the gas is in co-rotation, then the velocity structure of the absorption against stars in the Magellanic Clouds indicates that gas has been detected out to 10-15 kpc below the plane of the Galaxy. Electron collisional ionization models suggest temperatures around 10^5 K. This result has been confirmed by the discovery of C IV and Si IV in absorption at zero redshift against the quasar 3C 273 (refs. 12, 13, 14), showing that the highly ionized gas is globally distributed with comparable physical properties. N V has not been observed, placing a limit on the excitation temperature. The existence of this hot halo around our own (by definition, normal) galaxy strongly favors the interpretation of C IV and Si IV absorption systems, observed in the line of sight to high redshift quasars but at large velocity differences, as arising in the halos of intervening galaxies.

ACTIVE GALAXIES

Ultraviolet observations of active galaxies are valuable in revealing the presence of a hot star population, an ionizing non-thermal source, or resonance emission lines giving information on the physical state of ionized gas and the dynamics of the galactic system. Four individual cases are presented as examples of the kinds of problems investigated with IUE.

Extragalactic H II regions are either isolated systems or well-defined regions within a larger galaxy where active star formation is taking place. Observations of three of these faint objects with IUE (ref. 15), produced only upper limits in the Ly α emission flux in two of the cases, yielding a Ly α/Hβ flux ratio of less than 0.25. Ly α was detected in emission in the most metal-poor object with a flux ratio to Hβ of about 4, similar to that seen in quasars, but with a line width of ~ 150 km s^{-1}. A proposed explanation is the destruction of Ly α photons by dust in the more metal abundant objects, with concomitant reddening of the hot star continuum. The implication lies in the real difficulty in detecting primeval galaxies at high redshift, because they may be characterized by neither a strong ultraviolet continuum, nor strong ultraviolet emission lines.

NGC 1052 is an active elliptical galaxy with a compact nuclear radio source, strong optical emission lines, and a high M_{HI}/L_B. Observation with the short wavelength camera of IUE (ref. 5) shows no evidence of a non-thermal ionizing continuum. The only emission lines seen are C II] λ2326 and C III] λ1909, with no higher excitation lines. The observational picture is consistent with a shock heating model that brings the gas to around 10^4 K and cools it through the observed lower excitation UV and optical lines, although there is still some discrepancy in the predicted ultraviolet line intensities.

PKS 2158-380 is an example of a radio galaxy with extended optical emission lines, observed over a projected distance of 30 kpc. IUE spectra (ref. 16) show that the gas is in a high ionization state; the presence of He II λ1640 out to great distances suggests that the conditions are not like those of an H II region. The Ly α/Hβ flux ratio is consistent with the recombination value at the low density of $n_e < 300$ cm^{-3} found from optical [S II] line ratios beyond 4 kpc from the nucleus. A non-thermal spectrum of the form $f_\nu \propto \nu^{-1.3}$ is observed in the nucleus, and provides enough ionizing photons if the gas at 15 kpc radius can see them. The radio source is an asymmetric double with a position angle 50° different from the axis of rotation of the gas. The suggested morphology is that of a highly warped plane of gas, possibly produced by accretion onto a non-spherical potential with an axis different from any pre-existing symmetry axis.

The active galaxy and X-ray source NGC 7582 poses a problem: although strong optical emission lines are observed, the IUE spectra show a steep featureless continuum, with $f_\nu \propto \nu^{-3.4}$ (ref. 17). The 2200 Å depression yields a value for the extinction lower than that derived from the Balmer decrement, but the complete absence of ultraviolet emission lines favors the higher value. The evidence therefore suggests that the ratio of 2200 Å absorption strength to E_{B-V} may depart significantly from the average value in the case of this galaxy and by implication, possibly in others as well. This galaxy shows no Mg II emission, although on the basis of optical line strengths, it should have been detected at twice the quoted upper limit. The authors suggest that absorption must just cancel the emission.

QUASARS, SEYFERT GALAXIES AND BL LAC OBJECTS

These different manifestations of extreme activity in extragalactic objects are combined in order to discuss some common physical problems.

HYDROGEN EMISSION LINES AND THE PRESENCE OF DUST

A number of investigators have studied the ratio of Ly α/Hβ emission-line intensities in low-redshift quasars and Seyfert galaxies (refs. 1, 12, 13, 18, 19, 20, 21, 22, 23, 24). The combined result of all these measurements is that the ratio for broad emission lines is around 6, with a very small dispersion, while the simple approximation of optically thick radiative recombination predicts a value of about 40. The Hα/Hβ ratio and Pα/Hα ratio when measured (e.g., ref. 25) are more nearly consistent with the predictions of recombination theory.

The controversial question is whether selective extinction and reddening by dust is required to explain the observed line ratios, and, as a corollary, whether this dust is mixed into the broad-line emitting region or is intervening. For a lucid discussion of the problem and related ultraviolet observations, see ref. 26.

The presence of the λ2175 Å absorption feature at the emission-line redshift provides definite evidence for dust in some Seyfert galaxies. In 3C 120 (ref. 20), the inferred reddening of $E_{B-V} = 0.38$ is sufficient to account for the entire discrepancy from the recombination value. On the other hand, even though a substantial correction for dust is inferred for Mk 79 (ref. 20), I Zw 1 and NGC 7469 (ref. 24), it cannot account for enough "missing" Ly α photons.

Theoretically, dust is an attractive and efficient way to destroy resonantly trapped Ly α photons. Some observational evidence suggests that the He II λ1640/Ly α ratio is enhanced by a factor of two over the theoretical expectation (ref. 27), a result of the attenuation of Ly α by a small amount of internal dust. The problem is, that if enough dust were mixed into the broad-line region to produce the observed Ly α/Hβ ratio, He II and C IV would be strongly enhanced relative to Ly α, a result not observed (refs. 28, 29). The conclusion is therefore that the dust must be external to the broad-line region (ref. 30).

Two observational probes are suggested (ref. 30) to test for reddening by dust, neither of which is very sensitive to the details of temperature and density for conditions expected in the broad line emitting clouds. They are the recombination ratios of He II λ1640/λ4686 and O I λ1303/λ8446. The ratio for He II is observed to be 1.5 - 2 (e.g., ref. 26); this value corresponds to a differential extinction of $E_{B-V} \sim 0.3$, implying a factor of 6 to 8 correction in the Ly α/Hβ ratio. For 3C 273, a measurement of O I λ1303 yields $E_{B-V} = 0.26$ (ref. 26), while no λ1303 emission was detected in NGC 4151 (ref. 26). In several cases, the data are therefore consistent with a reddening by dust leading to a differential extinction of $E_{B-V} \sim 0.3$, an amount sufficient to account for the discrepancy between the observed Ly α/Hβ flux ratios and those predicted for optically-thick recombination.

Several lines of evidence, however, argue against dust as the sole responsible agent. The λ2175 Å absorption feature is seldom seen in quasar spectra at a strength comparable to that in 3C 120 or Mk79. As an example, the total correction for 3C 273 amounts to $E_{B-V} = 0.05$ at the source and $E_{B-V} = 0.04$ from the Galaxy (ref. 13). The discrepancy with the line ratio probes may lie in measuring difficulties, in establishing the true continuum level near the broad wings of Ly α and C IV λ1550. An attempt to separate the flux of strong line wings from the continuum in 3C 273 results in a measurement (ref. 13) of He II and O I ultraviolet line fluxes three times stronger than those quoted above, consistent with the low value of differential extinction inferred from the λ2175 feature. In addition, the data on Ly α/Hβ and Hα/Hβ flux ratios for 19 Seyfert galaxies (ref. 24) are not consistent with a narrow intrinsic range of emission-line ratios and variable reddening, and cannot be characterized by any single reddening sequence.

A general difficulty with dust is that the extinction is very sensitive to the amount of dust present. The Seyfert galaxy data (ref. 24), after correction for the differential extinction inferred from the λ2175 feature, show a scatter of only about a factor of two in the Ly α/Hβ ratios. Since a convincing argument has been made that much of the reddening must be external to the broad line region, a remarkably constant column density is required to produce the observed range of line ratios.

A different approach to the problem is to consider the energy budget. Selective destruction of Ly α radiation would lead to a significant excess of ionizing photons over the number of Ly α photons produced by recombination. The photon budget balancing depends slightly on the assumed continuum shape at the Lyman edge and strongly on the fraction of the sky covered by emission line clouds as seen from the continuum source. For 3C 273 (refs. 1, 12), if all the Lyman continuum photons out to 2 or 4 Rydbergs are converted to Balmer line emission plus Ly α, then Hβ is found to be deficient by a factor of 2-4 and Ly α by 10-20. Using the Hβ flux as a measure of the covering fraction, Ly α is then suppressed by about a factor of 5. If a statistical covering factor of 10% is used (ref. 23), then the Ly α flux is approximately consistent with its recombination value, and Hβ is enhanced by up to a factor of 5.

The enhancement of Hβ is favored in an analysis of the broad-lined radio galaxy, 3C 390.3 (ref. 22). It was cleanly decomposed into a broad emission-line component, with velocity width $\sim$ 5000 km s^{-1}, and a sharp line component with width $\sim$ 400 km s^{-1}. The Ly α/Hβ intensity ratio is consistent with Case B recombination for the sharp line component, whereas it is lower than that value by a factor of 16 for the broad line component. Interpreted in terms of a photoionization model including collisional excitation, Ly α is carrying its predicted share of the cooling, about 25%. The Balmer lines carry an unexpectedly large fraction, more than 30%; this fraction is comparable in the case of 3C 273.

Sophisticated line transfer calculations can reproduce the observed line intensity ratios without invoking dust. A thermal balance model treating photoionization and hydrogen excited-state population equilibrium (ref. 31) shows that ionization from excited states is significant in keeping the emitting cloud up to 1/3 ionized into high optical depths, with a consequent high electron density. At $\tau_{Ly\,\alpha} > 5 \times 10^6$, the Ly α line thermalizes by electron collisional de-excitation. It ceases to be an effective coolant, and the Balmer lines deep in the cloud are forced into that role. A careful treatment of the Ly α photon escape probability and frequency redistribution (ref. 32) yields the result that the Balmer lines and Paschen α arise from a region within in the cloud at $\tau_{Ly-c} \gtrsim 100$.

The perspective, then, is that there is evidence for dust, internal to the emitting clouds from the enhanced He II λ1640 emission relative to Ly α, and external from the λ2175 absorption feature. The narrow range in observed Ly α/Hβ intensities and the derived ionizing energy budgets suggest that the departure from simple recombination models is a line transfer effect through optically thick clouds, with a strong enhancement of Balmer line cooling.

THE FE II PROBLEM

A substantial fraction of low-redshift quasars and Seyfert galaxies show emission lines of permitted Fe II in the 4500 - 5200 Å region (refs. 33, 38). These lines arise from excitation of ground state and low-lying metastable levels to 5-6 eV levels, followed by radiative decay to 3 eV levels, with a branching ratio of about 100 to 1 favoring the ultraviolet resonance transitions. There is a marked similarity between Fe II and Mg II in both excitation potential and relative abundance, yet while the Mg II emission doublet at $\lambda 2800$ is a benchmark in quasar spectra, only upper limits were at first provided by IUE for the Fe II multiplets in either absorption or emission (refs. 1, 12).

Three mechanisms have been proposed to explain the presence of the optical Fe II lines (ref. 34). Radiative recombination is the least likely, unless the Fe abundance is anomalously high. Resonance fluorescence of continuum photons is a possibility with the optically thick emission-line clouds trapping the ultraviolet resonance photons, while the optical photons leak out. The observational consequence would be that $\sim$ 90% of the quasars show the ultraviolet resonance lines in emission, while the 10% with an optically thick cloud in the line of sight would show absorption. The theoretical difficulty is that with a covering factor as small as 10%, a very large turbulent velocity is required in each cloud to absorb enough continuum photons. Recent improvements in the collisional cross-sections for Fe II, incorporating improved atomic data and a more elaborate atom (refs. 35, 36, 39), show that collisions could be very important in populating the upper levels.

To study the situation, three extreme iron-line Seyferts, I Zw 1, II Zw 136, and Mk 231 were observed with IUE (ref. 37). The Fe II ultraviolet multiplets were clearly detected; the best estimate for the ratio of optical to ultraviolet photons is $\sim$ 3 for I Zw 1, $\sim$ 2 for II Zw 136, and 1-2 for Mk 231. These results are consistent with the predictions for collisional excitation, with high optical depth in the ultraviolet lines. The previous difficulty in detecting the ultraviolet Fe II emission probably results from the fact that these 12 multiplets are broad and of low contrast; and are easily seen only in places like the "blue wing" of Mg II emission. The question remains as to why only some quasars and Seyfert galaxies show Fe II; it may provide a sensitive probe of optical depth or electron density when the physical conditions are better understood.

ABSORPTION SPECTRA OF QUASARS

Quasars are sources of continuum emission against which intervening material can be detected in absorption over very long lines of sight. They therefore act as probes of both the local conditions of associated gas and the intergalactic medium. Unfortunately, high-redshift quasars are faint objects for IUE, so only the strongest absorption systems can be detected.

The discovery of Lyman-edge absorption at the quasar emission redshift signifies the presence of one of the optically thick emission-line clouds in the line of sight. The fraction of any randomly selected sample of quasars showing this absorption is an estimate of the covering factor, the fraction of the sky seen from the continuum source covered by optically thick material. None of a sample of seven high-redshift quasars observed with IUE (refs. 23, 44) showed Lyman edge absorption at the emission redshift. Ton 490 has a substantial Lyman edge absorption (ref. 40), but it may very likely be associated with a strong absorption system at 10,000 km s^{-1} shift to the violet. From a compilation of relevant IUE data (ref. 14), only one quasar out of 13 shows this Lyman-edge absorption, yielding a covering factor of $\sim$ 8%. This result is in good agreement with that from a sample of 30 very high-redshift quasars observed optically (ref. 41), a factor of $\sim$ 10%. As seen above, the determination of the fraction of continuum flux absorbed is critical to understanding the ionization structure and emission-line intensities of the quasar gas.

High-redshift quasars also provide a probe of the intergalactic medium and intervening gas associated with galaxies and clusters. In three cases (refs. 23, 42), flux has been detected below the He I ionization edge at λ504. The near-transparency of the intergalactic medium at these wavelengths requires that the helium neutral fraction be very low; collisional ionization models put a lower limit on the temperature of about 3 x 10^5 K (ref. 43). At least 75% of the high-redshift quasars observed with IUE (refs. 14, 23) show an optically thick Ly α - Ly edge absorption system along the line-of-sight, most with a velocity difference with respect to the emission redshift of order C. Follow-up optical observations (ref. 44) have revealed low excitation metal-lines plus weak C IV in these systems. Their line-of-sight density is $\sim$ 2 per unit redshift. With quasars as a probe, IUE observations can therefore sample the distribution of galaxies and associated halo gas at redshifts around 1.

THE CONTINUUM

BL Lac Objects

An obvious and essential property of BL Lac objects was revealed with the first IUE observations (ref. 1). The continuum flux is detected down to the wavelength limit of instrumental sensitivity as a continuation of the optical power law. No ultraviolet emission lines are detected, not even Ly α. Since the ionizing photons are present, the conclusion must be that the absence of emission lines is because of the absence of emitting gas. These objects therefore provide an uncontaminated look at the continuum source itself.

The combination of a power-law spectrum, detectable linear polarization of the optical light, and rapid time variability suggests a synchrotron origin for some of the continuum radiation in BL Lac objects (ref. 45). IUE observations in combination with measurements at many frequencies provide the critical sampling of the electromagnetic spectrum that will be necessary to discriminate among differing theoretical interpretations.

Mk 501 is one of the brighter BL Lac objects, and has been observed quasi-simultaneously at radio, infrared, optical, ultraviolet, and X-ray frequencies (ref. 46). The resulting spectrum shows a power law extending from ultraviolet to X-rays, steepening toward very hard X-rays. The flat spectrum radio emission cannot be an extension of that power law. A crucial step in the analysis is the separation of the power law from the dominant contribution of the optical and infrared light by the galaxy surrounding the active nucleus. Qualitatively different conclusions can be drawn depending on the method used (ref. 47). By removing a standard galaxy energy distribution, the power-law is seen to flatten off in the near ultraviolet and visual.

This spectral flattening may be interpreted as a reflection of the radio spectral turn-over, with the optical, ultraviolet and soft X-rays produced by "self-Compton" scattering of the radio photons off the relativistic electrons. Quantitative model fitting suggests a magnetic field of $\sim 4 \times 10^{-4}$ G and a variability time scale of $\sim$ 7 years. The steepening toward hard X-rays would reflect a high energy cut-off in relativistic electrons at $\sim$ 4 GeV. These data cannot rule out other models, however, such as inverse Compton scattering off hot thermal electrons, or two separate synchrotron components, one for the radio and one for the optical-ultraviolet.

Further observations show that neither the spectral energy distribution of Mk 501 nor a limited range of model parameters characterize all BL Lac objects uniquely. On the basis of simultaneous, multi-frequency observations of 0735+178 (ref. 48), the self-Compton model predicts an emission region size greater than 2.2 light years, but variability has been observed on a time scale of a week. In addition, the object I Zw 187 (ref. 48) shows an X-ray excess of a factor of 10 over the extrapolation of the power-law continuum, and emits such a low radio power that a magnetic field in excess of 10 G is required for inverse Compton scattering to be responsible for the higher frequency radiation.

The variable power-law component in Seyfert galaxies and quasars may be closely related to the BL Lac phenomenon. Multifrequency monitoring of the variability of two such objects, the quasar III Zw 2 and the Seyfert galaxy Mk 509, (ref. 49), shows that, while they have varied only at the 10% level in the ultraviolet, optical, and infrared, they have undergone substantial variations, in phase, in the radio and in X-rays. Further time-resolved observations may prove valuable in defining the relationship among components of the continuum emission.

Quasars

The optical and ultraviolet spectral energy distributions of quasars are more complex than those of BL Lac objects because of the presence of gas. From continuum points selected to be free of the effects of emission lines, an average optical-ultraviolet spectrum can be characterized by $f_\nu \propto \nu^{-0.6}$ (ref. 50). IUE observations of high redshift quasars (refs. 23, 44) show that below $\sim$ 1000 Å, the flat spectrum breaks and assumes the form $f_\nu \propto \nu^{-2.5}$ down to at least 400 Å. This steep spectral slope is a property of the continuum itself, as opposed to an effect of absorption or reddening, and is confirmed by optical observations of quasars with $Z > 3$. One implication of this result is that an extrapolation of the optical power law will overestimate the ionizing flux at 2 Rydbergs by a factor of 2-4.

A compilation of the entire spectral energy distribution of 3C 273 is shown in the Figure (ref. 13). The dot-dash line connected to the solid line of IUE observations is an empirical extrapolation (<u>not</u> a measurement), based on the assumption that the far-ultraviolet energy distribution of 3C 273 is similar to that of high redshift quasars observed with IUE. The Figure gives the impression that there is an excess of flux in the ultraviolet. The 3000 Å "bump" and Ly α two-photon emission can account for only a small fraction of that light. One proposed interpretation is that the ultraviolet radiation is a "thermal" excess, reminiscent of that seen in accretion disk binary stars (e.g. ref. 51). If the excess flux in 3C 273 could be characterized by a single temperature, it would be $\sim 2 \times 10^4$ K (ref. 13). Accretion-disk binaries exhibit a range in temperatures from $1\text{-}3 \times 10^4$ K. The high redshift quasars so far observed, however, seem to show the break in spectral slope at the same wavelength to within $\sim$ 200 Å. One possibility is that quasars have a closely regulated "thermal" emission mechanism near the continuum source. Another possibility to be considered is that a wavelength-defined effect may represent an atomic process not yet understood. Multi-frequency observations of other quasars will be valuable in addressing this question.

The results discussed here reflect the success of IUE in problems of extragalactic research and the promise of future space astronomy efforts.

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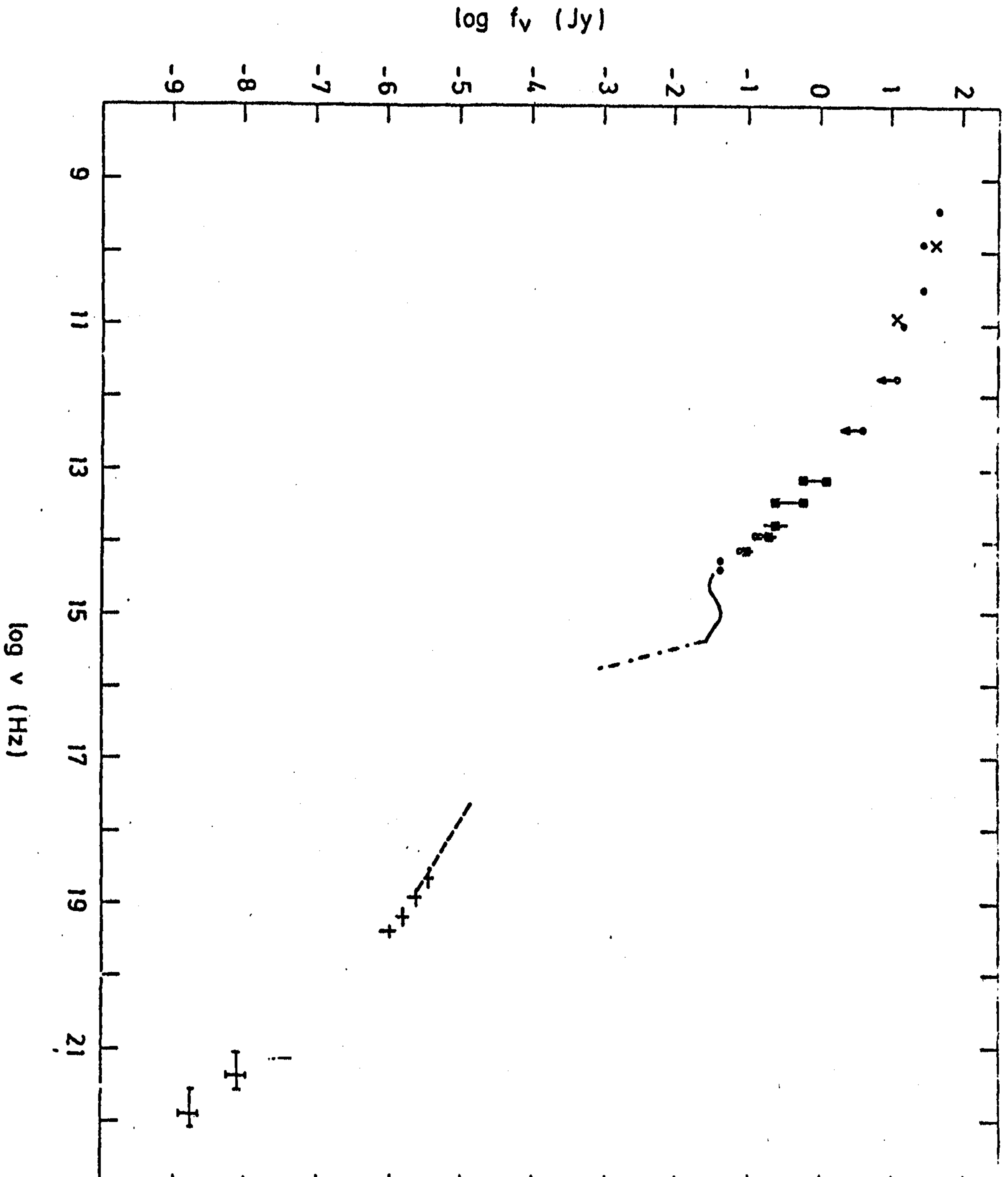

Figure 1