

Discovery of a Massive Old Galaxy at $Z = 3.4$

Simon Lilly (University of Hawaii) has used CFHT observations to discover in November 1987 an extremely distant radio galaxy which lies at a redshift of 3.395. As part of a program to study a dozen other sources in a sample of previously unidentified 1 Jansky radio sources, 0902+34 was identified with a faint 23rd magnitude blue galaxy using the PF RCA1 CCD camera in early 1986. The 1 Jansky sample, being at a somewhat fainter radio flux density limit than the 3C sample, was expected to contain radio galaxies at significantly higher redshifts than the highest redshift previously found for a galaxy in the 3C catalogue, that of 3C239 at $z = 1.8$. The 25% or so of the 1 Jansky sample that had remained unidentified after earlier CCD searches, and which were selected for study with the CFHT, were prime candidates for these high redshift radio galaxies. At about the same time as the CFHT identifications, observations were also made at infrared wavelengths with the United Kingdom Infrared Telescope (UKIRT). These resulted in the detection of 0902+34 at $K = 18.5$.

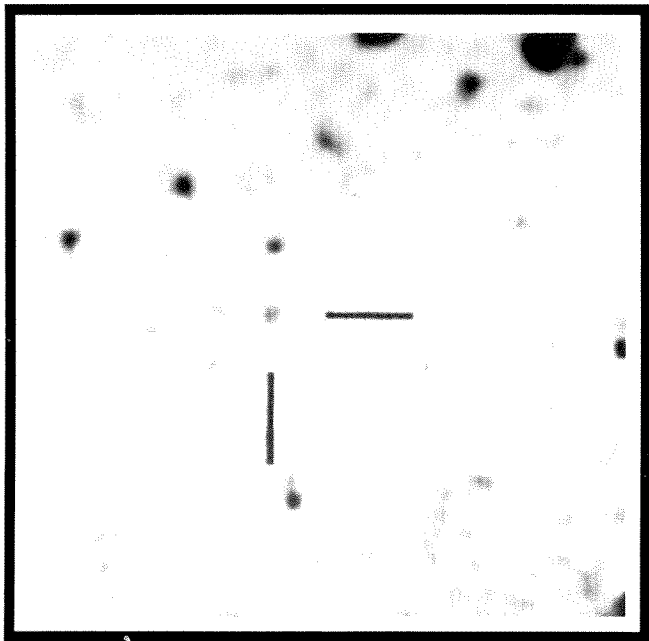


Figure 4: I-band image of 1 arcmin² centered on the 1 Jansky radio source 0902+34. The associated radio galaxy, which has $z = 3.395$, is shown. The galaxy is much brighter in the infrared waveband (equivalent to the rest-frame visual-band) indicating the presence of a substantial population of cool stars probably at least 1-2 Gyr old.

During the analysis of the larger sample, it was noticed that several of the properties of 0902+34 suggested that it might lie at an unprecedentedly high redshift. The faintness of 0902+34 in the infrared waveband and the redness of the infrared (J-K) colours could naturally be produced by a giant

elliptical galaxy at $z > 2$. The extreme blueness of the optical colors and a pronounced difference in morphology between the optical V-band and I-band images, indicated that the V-band might contain a very strong emission line, a line which would most plausibly be Lyman α at $z > 3$.

This idea was confirmed by a spectrum taken with a low-noise TI 800x800 CCD and the University of Hawaii Faint Object Spectrograph mounted at Cassegrain focus on CFHT. The spectrum (figure 4) showed very strong Lyman α and much weaker CIV 1549 Å at a redshift of 3.395. The presence of the weak CIV line has since been confirmed by other observers. At the time, this was by a wide margin the highest redshift ever recorded for a massive galaxy (as opposed to quasars or quasar companions). Consequently, this object represents a stellar population that is being seen at a much earlier cosmic epoch than has hitherto been studied. It should be noted that 0902+34 is known to be a galaxy, rather than a quasar, on account of the extended and clearly resolved continuum in the rest-frame far-ultraviolet waveband, and the very high equivalent width of the narrow Lyman α emission line.

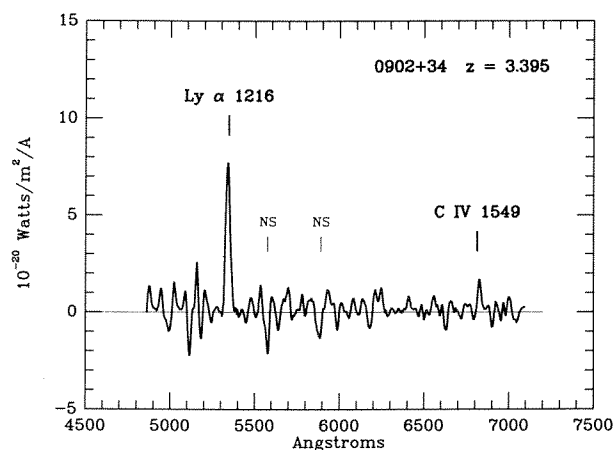


Figure 5: Spectrum of the radio galaxy 0902+34 showing strong Ly α and much weaker C IV 1549 Å at $z = 3.395$.

Like other high redshift radio galaxies at $z \sim 1.8$, 0902+34 is characterised by strong Lyman α emission and a luminosity in the rest-frame ultraviolet that is suggestive of a vigorous rate of star-formation. Probably the most interesting thing about 0902+34, however, is the red (I-K) color of 4.6 which implies a rest-frame visual luminosity that is much higher than that in the rest-frame ultraviolet. This indicates the presence of a substantial population of cool stars in 0902+34. A number of arguments indicate that these are most likely to be red giants from an evolved stellar population that is at least 1-2 billion years old. This older population would dominate the mass of the system, and hence, despite its high redshift, this galaxy is not believed to be a protogalaxy seen in the process of formation. The formation redshift of this 'old' population depends strongly on the assumed cosmological geometry, but is in excess of $z \sim 4.5$ even for an open, low q_0 cosmology, and would be much

higher for the popular 'flat' cosmological models favored by inflationary scenarios for the early Universe.

This discovery therefore confirms very directly the earlier indication from the existence of quasars out to $z \sim 4.5$ that at least some galaxies must have formed at $z > 4.5$. This is rather earlier than is expected in some popular theories of galaxy formation. It will be interesting to see whether more such objects are found, or whether old galaxies such as 0902+34 are in fact very rare at $z > 3$. Early reports circulating in the community suggest that many more such objects, some even more distant than 0902+34, are now being seen by other researchers.

While much work remains to be done, both on this galaxy and on finding other similar objects, the discovery is exciting because it represents the first time that a population of stars has been identified this far back in time. This is the first time that we have been able to study a galaxy at a redshift that is sufficiently high that it corresponds to an epoch close to that time in the early Universe when major phenomena, such as galaxy formation, the peak comoving density of quasars and so on, are expected to be occurring.

S. Lilly

New Insights on the Gravitational Lens System 2237 + 030

This system was first proposed as a gravitational lens candidate by Huchra et al. (1985, A.J., 90, 691) when they discovered a QSO at $z = 1.695$ at only $0''.3$ from the core of the Zwicky galaxy 2237+030 at $z = 0.0394$. The QSO was later observed to have at least two components by Tyson (1986, IAU Symp. 119, p. 551).

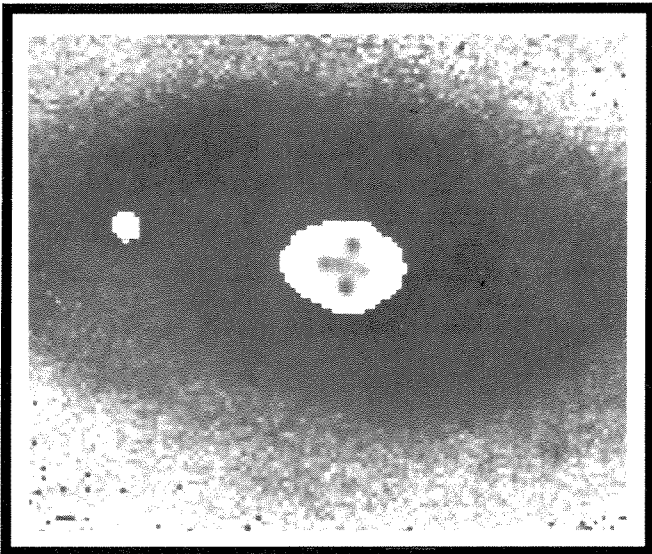


Figure 6: CCD image of the gravitational lens system 2237 + 030 obtained through an i (8000 \AA) filter at the prime focus of the CFHT under a $0''.65$ seeing FWHM. The scale is $0''.206$ pixel and the separation between the two brightest components is $1''.8$. The image is displayed in a logarithmic scale with a single wrap-around to show both the lensing galaxy and the 4 lensed quasar components.

Recent photometric and spectroscopic observations obtained at CFHT add important new information to confirming the gravitational lensing hypothesis.

First, direct images were obtained by H. Yee from University de Montreal on 25 September 1987 at the CFHT prime focus RCA4 CCD. Images in i , r and j bands were obtained with seeing of $0''.65$, $0''.90$, $0''.75$ respectively. Under this superb seeing, 4 components were observed at the QSO location with a $1''.8$ separation between the brightest ones (figure 6).

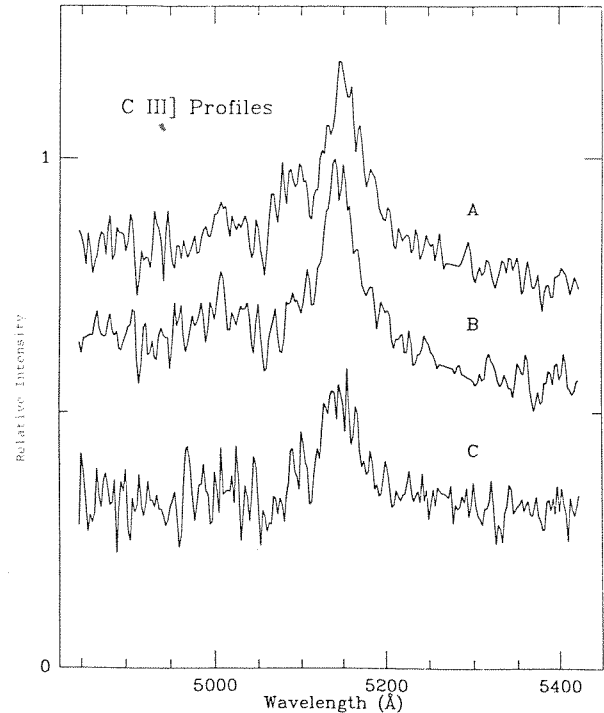


Figure 7: $C III] \lambda 1909 \text{ \AA}$ emission line spectral region for components A, B, and C. Data have been smoothed with a 2 point moving average filter. Component A has been arbitrarily shifted in intensity to avoid crowding. Profiles are the same to within errors.

Then, De Robertis and Yee observed the system with the Herzberg Spectrograph at the Cassegrain focus on 16 November 1987. Two slit positions were used to isolate only 2 components at a time, and an average seeing of $1''$ allowed them to show the similar structure of the $C III$ emission line for the 3 brightest components (figure 7, De Robertis and Yee, submitted to ApJ letters).

These new observations confirm that 2237 + 030 is indeed a gravitational lens system with the most unambiguous evidence for the lensing galaxy to date.

H. Yee