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High-Resolution Imaging of QSO 2305+187 (=4C 18.68)

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ABSTRACT. We present optical imaging of QSO 2305+187 with resolution ranging from 0.1 to 1.0 arcsec, in continuum and line emission. The data are from FOCAM and the HR Cam of the Canada–France–Hawaii Telescope, and the Wide Field Camera of the *Hubble Space Telescope*. These are compared with previously published optical and radio images. The QSO host galaxy has the basic properties of an elliptical, but has significant irregularities, and tidal tails which indicate an ongoing gravitational interaction with a close companion.

1. INTRODUCTION

The $z=0.313$ QSO 2305+187 (=4C 18.68) has been the subject of several detailed studies. The radio source is complex and asymmetrical, and has been considered as a precessing relativistic twin jet (Gower and Hutchings 1982; Gower and Hutchings 1986). While such a model fits much of the source structure, it does not explain the innermost radio jet, which is very straight, or the extended halo surrounding the object. The optical image shows an elliptical-shaped host galaxy and a close small companion (Hutchings et al. 1984), and a compact group of several galaxies which may be associated with the QSO. A narrow-band image in redshifted [O III] light by Shara et al. (1985) revealed a long, faint tidal tail and an extended ELR within the host galaxy.

It appears that this QSO may have been activated by a tidal event in the group of galaxies, and that the radio structure may trace some of the subsequent dynamics of the host galaxy. However, there is no good model for these events yet. Considering the variety of data and observables, the system appears to be an important one in understanding the triggering, fuelling, and lifetime of a QSO, and therefore warrants a more detailed examination. At this redshift, it is difficult to determine optical morphological details without resolution that is significantly better than 1 arcsec. Further clues on the state of the host galaxy in terms of tidal damage, general structure, relation with radio structure, dust, and star formation may be found with such data in the inner parts of the host galaxy.

Thus, in view of the richness of the existing database on this object, the complexity of its morphology, and the lack of detailed understanding of the QSO activation and environment, we have undertaken further high resolution optical imaging. The new observations are (a) broadband *I* filter image with the High-Resolution Camera (HR Cam) of the CFHT (McClure et al. 1989); and (b) Wide Field Camera (WFC) images with the *Hubble Space Telescope* using the 702W and 656N filters (see Griffiths 1990). The HR Cam data have FWHM of ~0.5 arcsec, and the WFC data have nominal resolution of ~0.1 arcsec, with the *HST* spherical aberration. The new data thus may yield complementary new information on the inner arcsecond or so of the QSO host galaxy.

The images are shown in Figs. 1, 2, and 4. We discuss the details below.

2. HR CAMERA DATA

The HR Cam observations were obtained in 1990 June at the prime focus of the CFHT. Two exposures of 600 s each were obtained with the I band filter and the SAIC low-noise CCD, with 0.13 arcsec pixels. The guide star was ~30 arcsec to the NW, and with the rapid guide and full telescope aperture the measured FWHM of the combined image was 0.5 arcsec. Photometric calibration was made from observations of a standard star field. In addition to the HR Camera data, we also report on an *R* band image taken in March 1986 with regular guiding (FOCAM) at the CFHT. This is one 600 s exposure with 1.0 arcsec FWHM, using the RCA CCD binned to 0.41 arcsec pixels. All these data were reduced and processed using the DAOVISTA.

The image that has the faintest limiting signal is the low-resolution (1 arcsec) *R* band (Fig. 1). In this, all the objects in the QSO group are resolved, but they do not lie within a large common envelope of low luminosity. (Gower and Hutchings 1986 find a large radio halo that is projected over some of the nearby galaxies.) The QSO host galaxy probably has a common envelope with the faint companion 4 arcsec to the NE, and the faint galaxy to the

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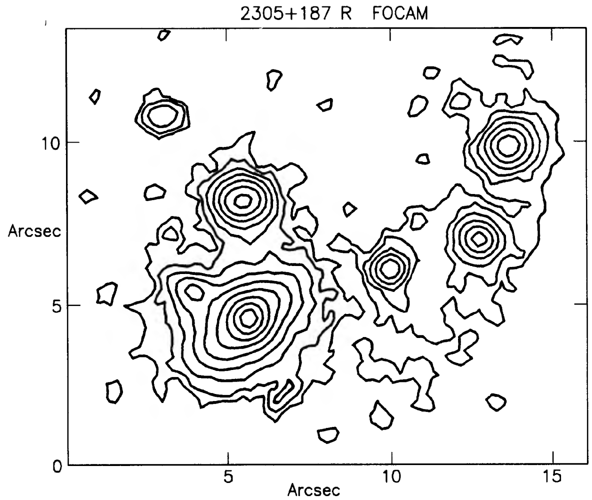

FIG. 1—FOCAM *R*-band image of 2305+187 field. N is up and E to the left. Contours are spaced a factor 2 apart, with a lowest level ~26.5 mag arcsec^{-2}. The QSO is in the large galaxy to the SE. Note the close companion to the NE, the faint elongated feature to the S, and the swept-back outer isophotes of the near companion to the W.

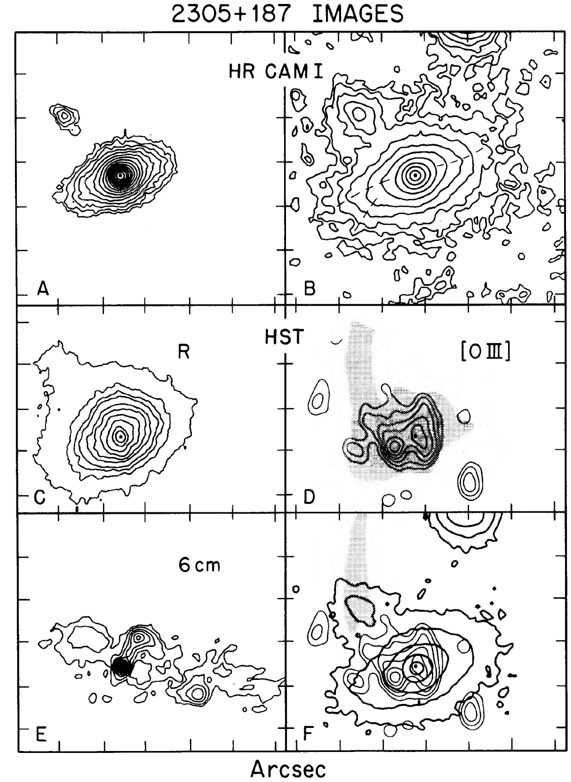

FIG. 2—Images of 2305+187 on a common scale. N is 15° to the right of up. (a) HR Cam inner image with contours 0.3 mag apart. (b) HR Cam outer image with contours 0.8 mag apart. Note the splitting of the long axis ridge to the SE and the wiggle to the NW; the asymmetry of the close companion; the host galaxy bulge to the N; and the curvature of the feature to the S. (c) Deconvolved *HST* WFC image. Note the consistency with the HR Cam image, and the N–S extension of the nucleus. (d) *HST* [O III] image contours. The QSO nucleus lies at the W central peak. The shaded region shows the outline of the [O III] emission from Shara et al. (1985). The main [O III] peak and its extension lie off-nucleus, and appear connected to the long tail. (e) Radio map from Gower and Hutchings. Note that no radio features coincide with the optical structure. (f) Superposition of the optical and [O III] structures. Note that the tail passes across the companion galaxy and that the [O III] bright spot lies on a region with brighter continuuum flux.

W has somewhat swept-back outer isophotes away from the QSO. The outer QSO host isophotes can be traced to some 7 arcsec along the long axis, where they are at ~26.5 mag per square arcsec. The shape of the luminosity profile is not well defined because of scattered nuclear light, the 1.0 arcsec resolution, and the close neighbor galaxies.

The HR Camera image [Figs. 2(a) and 2(b)] does not reach as faint by 2–3 mag but the shape of the luminosity profile is well defined in the inner part of the host galaxy (Fig. 3). This shows a good fit to an $r^{1/4}$ law, and not to an exponential. Both the FOCAM and HR Cam images give a ratio of nuclear to host luminosity close to 0.7, which is unusually small for a QSO: the host galaxy is luminous ($M \sim -22$) and the nucleus is weak for a QSO. The literature suggests that the nuclear luminosity may be variable by a magnitude (Hewitt and Burbidge 1980, 1987). Our CCD magnitudes for the QSO (nucleus plus host) are $R=17.8$ and $I=17.4$, but these are uncertain by several tenths because of nonphotometric weather.

It is instructive to look at other galaxies in the field. The brightest nearby galaxy is ~30 arcsec to the NW (galaxy A), close to a star (the HR Cam guide star). This object has similar shape and size to the QSO host, with similar brightness (excluding the QSO nucleus), but spiral arm structure can be seen in the HR Camera image (Fig. 4). The luminosity profile (Fig. 3) shows a well-defined exponential fall-off, and does not fit an $r^{1/4}$ law. The galaxy 7 arcsec to the N of the QSO on the other hand, which is smaller and a magnitude fainter, has elliptical isophotes and has no resolved structure. Its luminosity profile fits an $r^{1/4}$ law and not an exponential. Thus, we are able to determine the galaxy type characteristics with some confidence in objects of this size and brightness.

We therefore can take seriously the result mentioned above that the QSO host fits an $r^{1/4}$ law. The smooth shape and lack of evidence for spiral features are further evidence that the host galaxy is like an elliptical. However, but there are some significant deviations from a smooth elliptical shape. In the faintest isophotes, seen in both the FOCAM and HR Cam images, there is a luminous extension toward the N, to the W of the faint close companion, which can be seen out to some 3 arcsec. This is roughly normal to the host galaxy long axis. In the FOCAM image there is a faint object extended EW, to the S of the QSO host galaxy. In the HR Cam image this is seen to be a narrow curved feature [Fig. 2(b)], one end of which points at the QSO nucleus. The HR Cam data also show that the outer isophotes at the SE end of the long axis split into two branches instead of a smooth ellipse. Finally, the isophotes in the inner well-exposed part of the host galaxy show a wiggle of their outer turning points to both the NW and SE, as sketched in Fig. 2(b). These wiggles do not resemble the inclined spiral structure seen in the bright nearby galaxy A.

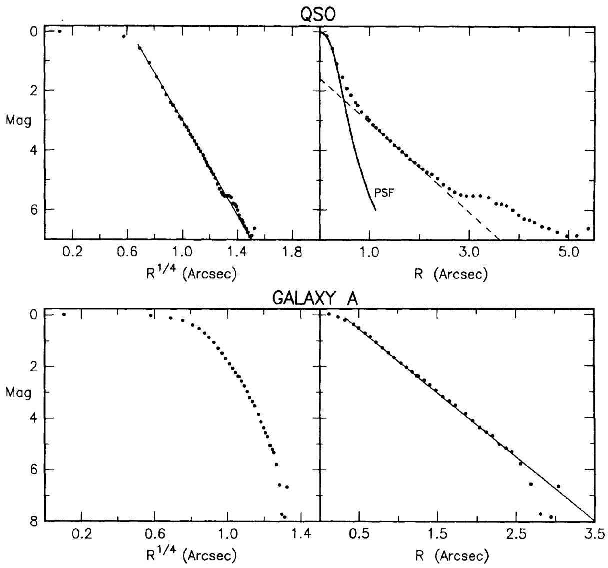

FIG. 3—HR Cam azimuthally averaged luminosity profiles of 2305+187 and the galaxy 35 arcsec to the NW. The bulge in the QSO curves is due to the nearby companion galaxy. The QSO light fits an $r^{1/4}$ law well, while the (spiral) galaxy fits an exponential.

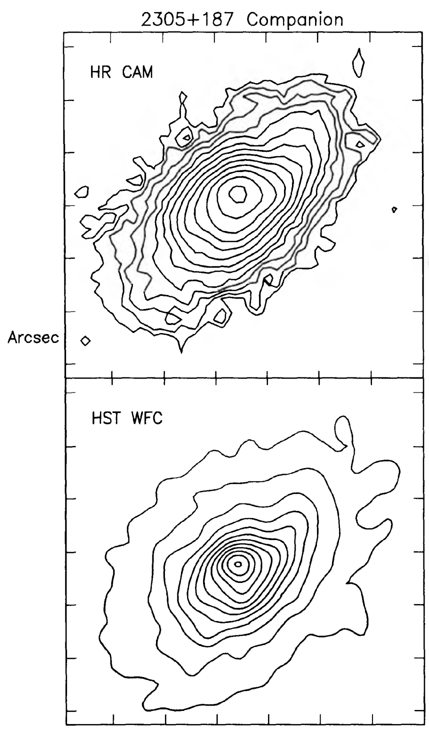

FIG. 4—Images of the field galaxy A. The upper image is from HR Cam and the lower is the *HST* (raw, smoothed over 0.2 arcsec). Contour levels are at equal ratio intervals, chosen to reveal the structure clearly. There is little difference between the two in the detail revealed. The galaxy appears to be a barred spiral, with the bar aligned close to the line of sight.

In addition to the structure of the host galaxy, we can see that the faint companion 4 arcsec to the NE is quite asymmetric, as well as lying in a common halo with the QSO host.

3. THE *HST* IMAGES

The *HST* observations were obtained in 1991 June and consisted of a 230 s exposure with the 702W filter, and two 600 s exposures with the 656N filter. The latter observation was taken to observe the redshifted [O III] 5007 Å line. The telescope guiding during the observations was nominal. These data were processed using standard flatfields, and reduced and measured with IRAF.

The narrow-band image is very weakly exposed. However, there is clearly extended emission from the QSO, and a point source at the nearby star. The NB and continuum images can be registered by using the star, to establish the superposition of the QSO images. Figure 2(d) shows the smoothed NB image, after cleaning of the cosmic rays. We have not attempted any spatial deconvolution as the signal is too weak. We also show schematically the ground-based NB image of Shara et al. (1985), in which a faint tidal tail is seen as well as bright extended emission of [O III] within the host galaxy. The *HST* image is too weak to be reliable in the faint parts, but it does show that the brightest part of the [O III] emission lies away from the QSO nucleus. There is a secondary maximum close to the QSO nucleus. The main peak lies along the curve defined by the faint tail and within the bright part of the Shara et al. image. Thus, there appears to be a secondary "nucleus" of bright line emission within the QSO host galaxy. This peak does not correspond with any radio feature, but the ground-based continuum images do show a region of higher luminosity at this spot (see below).

In the *HST* continuum image, the star 30 arcsec to the NW clearly shows the *HST* spherical abberation, and we have performed Lucy–Richardson deconvolution of the data using this as the point spread function (PSF). Because the WFC PSF is spatially variable, we also deconvolved with a calculated PSF for the QSO location, from the PSF library using the STScI Telescope Image Modeling (TIM) software. The polychromatic model calculated for the F702W filter using an A0 star was used. In both reconstructions, the algorithm was run for 15 iterations (limited by the relatively low S/N). The Lucy–Richardson method (Lucy 1974; Richardson 1972) preserves flux, and tolerates small errors in the PSF. The comparison of the two deconvolved images gives an empirical way of assessing what features are sensitive to the procedure, and what features are likely to be real. We have done this for the nearby field galaxy A as well, which lies close to the first PSF star.

In the case of the QSO, the central light source is bright enough to cause spherical-aberration contamination of the fainter host galaxy, and deconvolution offers significant improvement in the central part of the galaxy where the signal is high. Figure 2 compares the HR Cam and *HST* image. The main morphological features and the photometric properties are the same with both PSFs used, although the specially tailored PSF for the QSO yields a cleaner looking image. In Fig. 2(c) we have used the *mean* of the two images as this retains the features which are common to both, and hence more likely to be real. However, we stress that the differences are small.

The *HST* image shows a N–S extension to the innermost isophotes. This is not resolved with HR Cam, but does line up with the northerly extension of the outer isophotes seen in both images, which we have already mentioned. In the innermost 0.25 arcsec, the *HST* deconvolved data show the nucleus to be displaced to the W of center, which is not seen in the star. However, there is no indication of this asymmetry in the raw image, and we are not convinced of its reality.

In the main body of the host galaxy, the *HST* outer isophotes are more rounded than the HR Cam, but the shape of the asymmetrical features agree well. Outside of ~ 3 arcsec radius the ground-based data are better because of greater S/N. The splitting to the SE and the locus of the long axis to the NW are common to both data sets.

We have examined the photometric properties of the *HST* continuum image. The deconvolution has the effect of putting outlying signal into the center. Thus, different radii must be used to compare the raw and deconvolved fluxes. In the case of 2305+187, the light from the nearby companion and halo is moved into the central area, leading to an apparent increase of overall flux. The peak signal value rises from ~ 300 in the raw image to ~ 1200 in the deconvolved. Overall, the luminosity profile is altered significantly, and careful comparison of the profiles of the QSO, the companion galaxies, and the PSF star shows that for this level of signal and size of object, we cannot derive a meaningful luminosity profile. Thus, the HR Cam data are of much greater use in this instance. It may be that careful deconvolution of a high signal *HST* image would be reliable, but such data would require an order of magnitude larger exposure than we have here (of order an hour). In terms of information gathering power as a function of telescope aperture, this compares with the 20 min exposure on the 2 times larger CFHT.

Superposing the narrow-band and broadband images shows that there is a region of brighter light in the continuum image at the location of the [O III] bright spot. As shown in Figs. 2(d) and 2(f) the [O III] tail appears to originate at this point. We have also attempted to estimate the continuum contamination of the weak narrow-band image. From the bandpass and sensitivity data for the filters and the relative exposures, we estimate that some 20% of the 2000 DN in the narrowband signal of the QSO, is continuum.

Figure 4 shows the nearby galaxy A as seen by the HR Cam and *HST*. The structure of the galaxy is equally resolved in both, although the *HST* central cusp is significantly sharper. It appears that the main structure of the galaxy is resolved at the 0.5 arcsec level. In the *HST* data, the signal is not high enough and the central light source is not bright enough for the deconvolution to offer significant improvement in resolution. The main arm of the galaxy is seen to pass to the S of the nucleus. Visual inspection of the images on a screen have the appearance of a barred spiral viewed almost along the bar, and this appears to be a fully consistent description of the galaxy.

4. DISCUSSION AND SUMMARY

Our new observations have yielded information on the small-scale structure of the QSO and its companions. The QSO host galaxy has the overall luminosity profile of an elliptical galaxy, but there are significant irregularities in the red light structure. The faint tails and wiggles along the long axis indicate that the galaxy has undergone a merger or tidal event. The heavy dust lanes characteristic of recent interactions would be visible in the new data, and are not seen. This, the minor nature of the morphological irregularities, and the presence of the extended ratio structure, all suggest that the tidal event is relatively "old" (10^8 yr: see Hutchings and Neff 1991). Gower and Hutchings (1986) also discussed timescales and suggested several times 10^7 yr as the halo age.

The emission line morphology is considerably more complex and irregular. This, however, is not uncommon in radio-loud QSOs (see, e.g., Stockton and MacKenty 1987). We are able for the first time to relate the [O III] and continuum structures of this QSO in detail. For example, the faint tail detected by Shara et al. passes directly "through" the close companion galaxy [Fig. 2(f)]—always bearing in mind that this may only be a projection—and suggests, in addition to the continuum morphology, that there is an ongoing tidal interaction between the QSO host and this object. We also find that there is an off-nuclear bright knot of [O III] emission that is connected with the long tail. This bright knot is seen faintly in the continuum images (not including the [O III] line). We note that the inner radio jet (Gower and Hutchings 1986) is resolved at the 0.1 arcsec level, and is seen right into the nucleus, so that the radio beam is very well defined. We see no corresponding optical structure.

Since the [O III] is the result of photoionization of low density gas, it may be illuminated by nuclear light or hot stars. Figure 1 shows faint signal along the path of the tail which indicates a very low level (if any) of continuum flux (the [O III] line lies in the filter bandpass). Thus we assume that the [O III] is ionized by nuclear radiation. The shape of the [O III] tail may then be caused by beaming of the nuclear radiation, or it may show the actual distribution of gas which is uniformly illuminated. Since the shape is curved and not aimed at the QSO nucleus, we conclude that this is a real wisp of gas and that the nuclear radiation is not significantly beamed in that direction. The bright knot within the host may be illuminated by a beam, but it does not lie in a radio beam or within a radio-bright knot. The continuum here is not very blue (although we do not have a large continuum wavelength leverage), so again we think this is a real condensation of gas within (or projected on) the QSO host. Hutchings et al. (1984) quote $B-V = 0.1$ for the nucleus and 1.4 for the whole host galaxy, from photographic data. This suggests that there is not a significant population of young stars present. However, the origin of the [O III] gas presumably does lie in the tidal history, and it may in future be the site of massive star formation.

The curved tail to the S, on the other hand [Figs. 1 and 2(b)], is seen in continuum and not line emission, and is likely to be composed of old stars spread out by tidal effects. We also note that the second neighbor galaxy (to the NW) has swept-back morphology (see Fig. 1) which suggests "knowledge" of the QSO, although there is no connecting luminosity. This galaxy does lie on the limb-brightened edge of the radio halo (Gower and Hutchings 1986), and we may possibly be seeing an interaction between the outer parts of this galaxy and the expansion of the radio-emitting halo. While this too is a projection, this appearance is consistent with a physical association over a reasonable range of distance along the line of sight.

The system appears to be one in which there is an ongoing tidal interaction with at least one companion galaxy. It is likely that the sequence of events in this compact group has been rather complex. The complex radio morphology suggests that these events are felt in the nuclear engine, causing several changes of direction of the radio axis. The irregularities in the host galaxy suggest that the effects are also felt throughout the body of the stellar population, and that there is significant interstellar gas in the inner galaxy with a very irregular distribution. We feel that further major progress in studying this system will need a combination of high signal and 0.1 arcsec resolution over a range of colors, and in selected emission lines such as [O III], [O II], or Hα.

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