THE ASTROPHYSICAL JOURNAL, 473:760–762, 1996 December 20

THE HOST GALAXIES OF *IRAS*-SELECTED QUASI-STELLAR OBJECTS[1]

P. J. BOYCE AND M. J. DISNEY
Department of Physics and Astronomy, University of Wales College of Cardiff, P.O. Box 913, 5 The Parade, Cardiff CF2 3YB, UK

J. C. BLADES
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

A. BOKSENBERG
Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, United Kingdom

P. CRANE
European Southern Observatory, Karl Schwarzschild Strasse 2, D–8046 Garching, Germany

J. M. DEHARVENG
Laboratoire d'Astronomie Spatiale du CNRS, Traverse du Siphon, Les Trois Lucs, F–13012 Marseille, France

F. D. MACCHETTO
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

C. D. MACKAY
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, United Kingdom

AND

W. B. SPARKS
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

Received 1996 April 9; accepted 1996 July 15

ABSTRACT

We present *Hubble Space Telescope* (*HST*) images of three QSOs selected on the basis of their *IRAS* properties. The data were taken with the Planetary Camera primarily in order to examine the host galaxies. All three QSOs appear embedded in spectacular interactions between two or more luminous galaxies, probably spirals. We discuss the evolutionary connection, if any, between these three objects and the far more numerous ultraluminous infrared galaxies. We argue that these three objects are probably young and therefore do not fit a scenario in which QSOs emerge only in the later stages of an interaction when most of the dust has been blown away. It may be that we are simply viewing them from a fortuitous angle that allows a clear view into the cores.

Subject headings: galaxies: active — galaxies: interactions — galaxies: nuclei — galaxies: starburst — infrared: galaxies — quasars: general

1. INTRODUCTION

Imaging QSO host galaxies at high resolution has always been a principal scientific goal for the *Hubble Space Telescope* (*HST*). Less than 20 have been observed so far (Bahcall, Kirhakos, & Schneider 1994, 1995a, 1995b, 1996; Hutchings et al. 1994; Hutchings & Morris 1995; Disney et al. 1995; McLeod & Rieke 1995) and the great majority of those resolved have turned out to be early type L^* galaxies undergoing interactions.

The QSO candidates observed so far have come from a variety of QSO types including the luminous, radio-loud, radio-quiet, X-ray, etc., but only one of the rare *IRAS*-selected QSOs, IRAS 14026+4341 (Hutchings & Morris 1995), has been published. It would appear to be an early type, interacting with a fainter companion.

The *IRAS*-selected objects should be especially interesting: (1) because presumably they include large amounts of dust and therefore later type hosts and (2) because of their possible relationship to the ultraluminous infrared galaxies, which are far more common in space. It has been speculated that QSOs may be a late, transitory phase in the merger of some spiral galaxies, after the dust has been blown away by the AGN but before all the fuel resulting from the merger has been used up (e.g., Sanders et al. 1988; Hutchings & Neff 1988, 1991).

Our three sources are all QSOs taken from the lists of Low et al. (1988, 1989), who selected 12 such objects from 14,000 square degrees of sky on the basis of their warm 25 μm/60 μm colors, their stellar images on the POSS and the breadth of their emission lines (>5000 km s^{-1} FWHM). All happen to be very luminous ($L_{\rm IR} > 10^{12}\ L_{\odot}$) IR sources.

We find that all three appear to be the result of spectacular collisions between two or more luminous galaxies, probably spirals.

2. OBSERVATIONS

Observations, each comprising one orbit ($\sim$1800 s) subdivided into three or four shorter exposures, were made through the F702W filter, which corresponds roughly to the *R* band, with the Planetary Camera (Trauger et al. 1994). This camera-filter combination was chosen for its high relative sensitivity to galaxy light and because it has sufficient resolution and dynamic range to reduce saturation in those critical areas of the image where QSO and galaxy can be most easily disentangled.

To illustrate the relative strengths and weaknesses of the *HST* data Figure 1 (Plate 18), our image of one object, should be compared with the corresponding ground-based image in Figure 2 published by Hutchings & Neff (1988). The *HST* image shows far more detail on the subarcsecond scales close to the AGN: the ground-based image, taken with a 4 m telescope, has much higher signal to noise further out, enabling one to see the low surface brightness merger

[1] Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

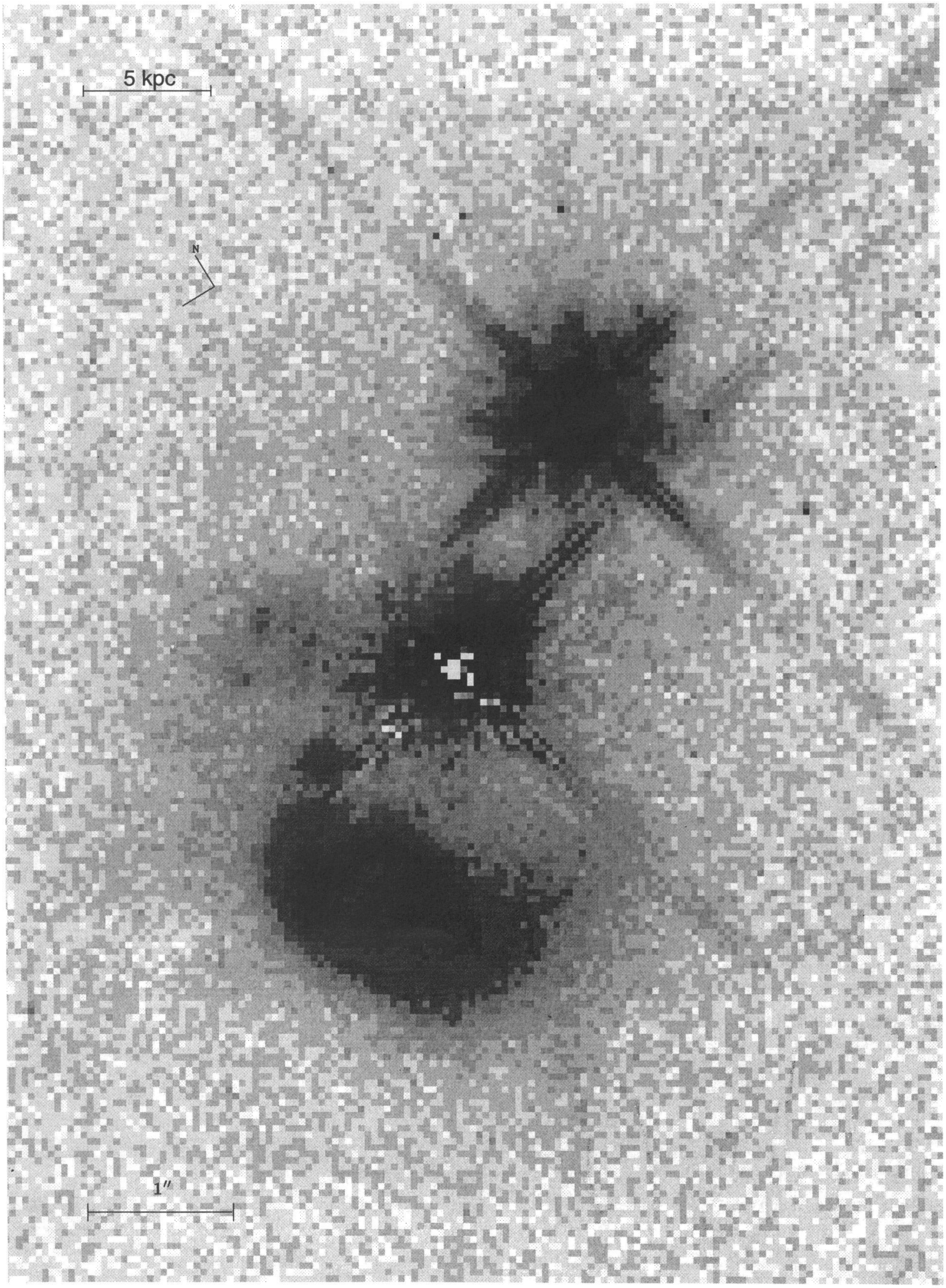

FIG. 1.—PC image of IRAS 04505−2958

BOYCE et al. (see 473, 760)

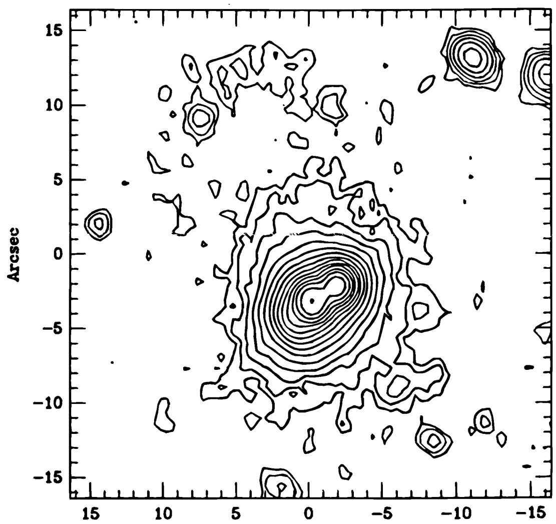

FIG. 2.—Ground-based *R*-band CCD image of IRAS 04505−2958 taken from Hutchings & Neff (1988).

TABLE 1

PROPERTIES OF THE THREE *IRAS* QSOs

	04505−2958	13218+0552	07598+6508
Data from Previous Work			
L(IR) in $L_{\odot}$[a]	1.4×10^{12}	1.1×10^{12}	1.2×10^{12}
L_{IR}/L_{opt}[b]	3.6	91.0	5.3
$F(25)/F(60)$[a]	0.25	0.25	0.35
m_R[c]	15.8	17.9	15.3
z[c]	0.286	0.190	0.150
HST Data			
L_{host}/L_{QSO} (in R)	0.6	5	0.2
$M_{host}(R)$[d]	−22.0	−19.9	−20.2
L_{host}/L^*	∼6	∼1	∼1

[a] Taken from Low et al. 1988.
[b] Taken from Low et al. 1989.
[c] Taken from Veron-Cetty & Veron 1993.
[d] Assuming $H_0 = 75$ km s^{-1} Mpc^{-1}, $q_0 = 0$.

plume 15″ to the north, which is undetected with the *HST*. The two kinds of data are clearly complementary, but, as expected, the *HST* is better at discriminating the hosts themselves.

In our earlier observations (Disney et al. 1995) we found cross-correlation to be the best way of categorizing hosts. Here the hosts are much easier to distinguish and highly disturbed so that no simple cross-correlation model would fit. Instead we have performed a simple subtraction of a model PSF generated by the Tiny Tim software package (Krist 1993). The scaling factor in each case was chosen so that, after subtraction, the residual "galaxy" image continued to increase monotonically to the smallest radius at which the image was not saturated on the shortest exposure. Although fairly crude, experiments showed that the technique yields a probable error on the ratio of (QSO/host) luminosity of no more than 20%. None of the images was saturated beyond a radius of 5 pixels in the shortest exposure, and most do not suffer saturation outside the central 3 pixels.

3. INDIVIDUAL OBJECTS

The upper part of Table 1 shows the properties of the three objects as determined by Low et al. (1988, 1989); the lower part shows inferences made by us from the *HST* images.

IRAS 04505−2958.—Figure 1 shows two bright components separated by 1″.6, the northernmost of which is known to be (Low et al. 1989) a foreground G star. There is a striking ringlike feature 1″.5 to the SE of the nucleus, a second clear "blob" 1″ E of the nucleus with four or more other distinct but less luminous blobs beside it.

We interpret the image as a violent interaction between two galaxies, one at least of which was spiral. The ring may be the ring galaxy left behind when one galaxy plunges vertically through the plane of a spiral (Lynds & Toomre 1976). It is unlikely that a giant elliptical is involved either in this or in the other two examples, for ellipticals are strongly clustered, and we find no elliptical of the right magnitude on any of the adjacent Wide Field frames. In this picture the prominent blob could be the displaced nucleus of the ring galaxy, the lesser blobs sites of star formation.

The sum total of host light, excluding the QSO itself, is considerable (∼6 L^*; $H_0 = 75$ km s^{-1}, $q_0 = 0$ used throughout), which may betoken the involvement of two giant spirals but with only one stellar nucleus beaming in our direction. The luminosity of the QSO, which of course does not show up in Figure 1, is 10 L^* in the R band and about 200 L^* altogether, including the FIR.

The projected distance between the QSO and the center of the ring is ∼5 kpc, so that if the interacting galaxies collided at no more than 500 km s^{-1}, the one passed through the plane of the other less than 10^8 yr ago.

IRAS 13128+0552.—According to Low et al. (1988) this has an $L_{IR}/L_{opt} = 91$, making it the "reddest known quasar"; its $(B-K) = 7^m.2$. Our image (Fig. 3 [Pl. 19]) confirms that the nucleus is weak at R but is elongated by 6 pixels (∼1 kpc) in the SSW direction. It could be that there are two distinct nuclei, one far weaker than the other. Further out there are distinct loops and contrails suggestive of a previous complex interaction spread over several orbits, but with no sign of interaction with the obvious spiral 6″ to the SW.

The outermost trails in the image appear to be at a projected radius of 12 kpc arguing for a maximum interaction age of ∼12 kpc/500 km s^{-1} ∼ 10^7–10^8 yr. However, if we take the 1 kpc of the elongated nucleus as the relevant length scale then the timescale is reduced to 10^6–10^7 yr. Altogether the image is strongly suggestive of a merger between two galaxies of roughly equivalent mass, one at least a spiral, which has either just concluded or is about to do so.

The magnitude of the host at R is just L^*, and as the nucleus is 5 times fainter, this object does not strictly qualify as an optical QSO, only as a type I Seyfert. However, from the colors, it is highly obscured, and as the peak of our emission is no more than 1 pixel (175 kpc) wide it almost certainly contains a much more luminous buried QSO.

In its shape, size, infrared output, and luminosity, this object bears a remarkable resemblance to Markarian 231, also thought to be a buried QSO (Armus et al. 1994; Lipari, Colina, & Macchetto 1994; Hutchings & Neff 1987, Hamilton & Keel 1988).

IRAS 07598+6508.—This is an apparently brighter object ($m_R = 15.3$) than the other two with a relatively fainter host ($L_{host}/L_{QSO} \sim 0.2$ at R). Scattering and saturation therefore make it a more challenging object in which to

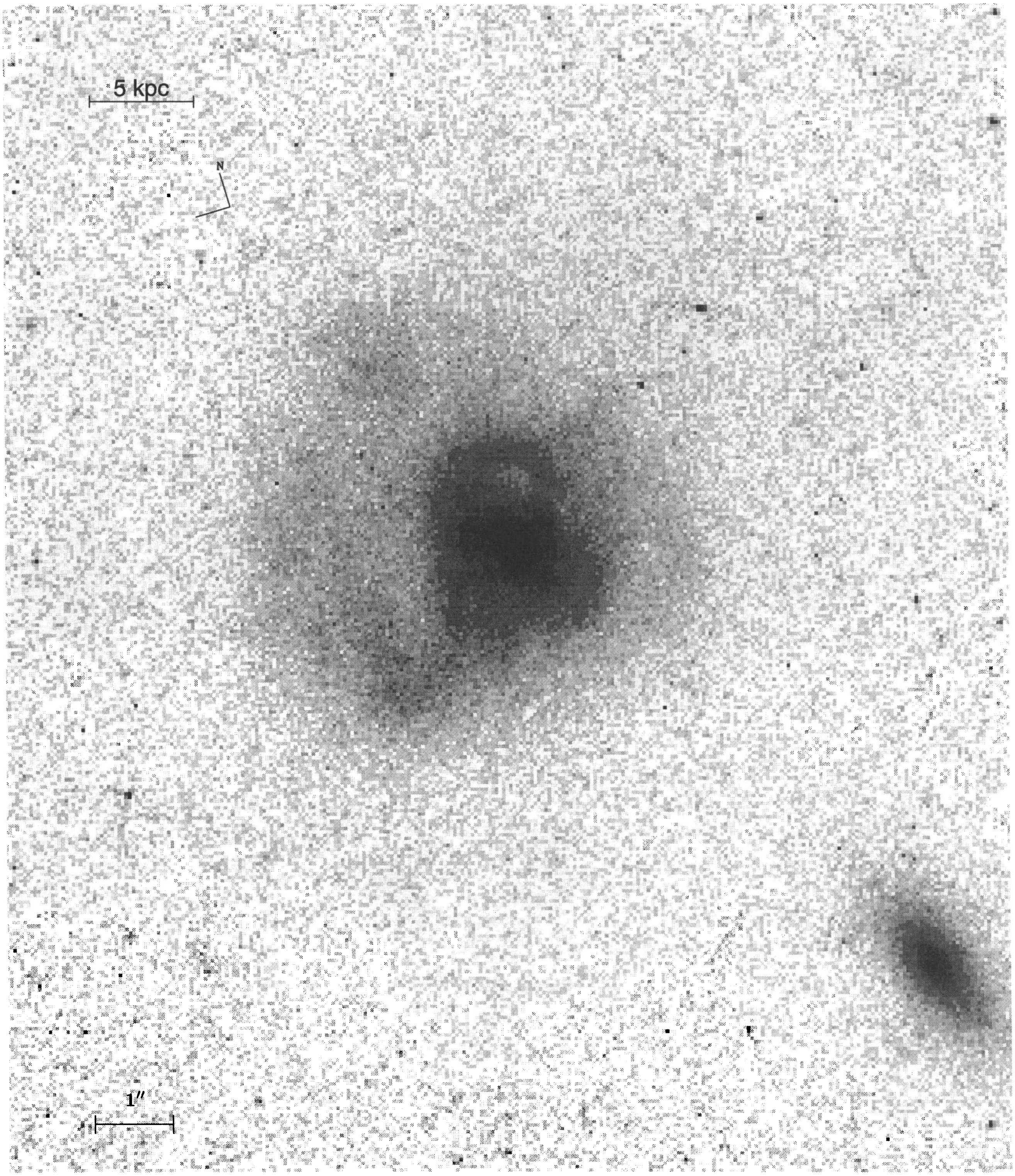

FIG. 3.—PC image of IRAS 13218+0552

BOYCE et al. (see 473, 761)

detect structure close to the nucleus. Further out, one can see (Fig. 4 [Pl. 20]) complex and irregular features stretching out as far as 40 kpc (10″) from the nucleus. The emission is patchy, with a low surface brightness (22 R mag arcsec^{-2}), but is reminiscent of tidal debris resulting from an interaction that might have taken place 40 kpc/500 km s^{-1} $\sim 10^8$ yr ago. Uncertainties in the host luminosity are rather larger here (± 50%) but it is roughly L^* at R. The $L_{\rm IR}/L_{\rm opt} \sim 5$ for the object as a whole is typical of the Low et al. QSOs.

4. DISCUSSION

As a group and as individuals, these three *IRAS*-selected QSOs appear to be different from the great majority of other QSOs so far observed with *HST*. They involve at least one gas-rich giant galaxy and possibly two, since there appear to be no giant ellipticals in their environment while the apparent violence and complexity of the images suggest that mergers, and not mere interactions, are involved. However, in view of Hutchings & Morris's (1995) *HST* observation that another such object (IRAS 14026+4341) is a bright elliptical in the early stages of an interaction with a smaller companion, it is too early to generalize. Further *HST* observations of this rare and interesting QSO class are urgently called for.

How are these QSOs related to the ultraluminous *IRAS* galaxy sample (Sanders et al. 1988), objects which have a similar FIR output, but which are much commoner in space? They too are interacting systems, and Sanders et al. (1988) suggested a natural evolutionary process in which mergers give rise to a buried QSO, seen as a luminous IR galaxy, which only appears as an optical QSO later on when the obscuring dust in blown away. Subsequent observations (e.g., Carico et al. 1990; Hutchings & Neff 1991; Majewski et al. 1993; Lipari et al. 1994; Armus et al. 1994) suggest a more complex situation in which only a small fraction of luminous *IRAS* sources finish up as QSOs.

According to the Sanders et al., scenario our objects ought to be in the late stages of an interaction with much of the dust blown away. In discussing the relevant observations much depends on the tricky and presently subjective judgement of the stage which an interaction has reached. Hutchings & Neff (1991) for instance have used morphological criteria to divide their interactions into strong versus weak and new versus old. By their criteria our three objects would appear to be "strong new" interactions. Likewise the timescales we adduced in § 3 are suggestive of young interactions. In that sense our objects do not fit the Sanders et al. scenario which would predict that they be old. We would simply comment that a selection effect may operate here. Luminous optical QSOs will make it impossible to see (in the optical) the evidence of mergers close to the nucleus. In picking a merger timescale, as we and others have done, by dividing the size of the interacting structure by a common merger velocity, luminous optical QSOs will perforce look older because the inner structure, such as the ring in IRAS 04505−2958 will be swamped by QSO light. More *HST* observations capable of seeing close-in are called for here. The way ahead lies in detailed comparisons between individual observations and interaction simulations covering a wide parameter space. It is very encouraging that structures as complex as the ring in IRAS 0450−2958 and the loops around IRAS 13128+0552 can be clearly picked out with *HST*. Such comparisons may eventually lead to detailed merger scenarios.

Although these objects are optical QSOs (IRAS 13128+0552 barely so, being more properly a Seyfert I) most of their energy still appears to be reprocessed on dust (99% of it in the case of IRAS 13218+0552), which will rapidly cool when the heating source is removed. Seen from most angles therefore these objects might not be classified as optical QSOs at all. The rarity of *IRAS* QSOs compared to ultraluminous IR galaxies may simply reflect the fact that we see such QSOs only through small holes in their dust cocoons. In other words, we could be dealing with a geometrical rather than an evolutionary sequence. In the case of IRAS 13218+0552 a tiny change in viewing angle might extinguish the already weak QSO signal altogether.

We should emphasize that these *HST* observations are not easy. The presence of scattering (Krist & Burrows 1994) and saturation in the present camera make it difficult to work close to luminous QSOs. It is worth recalling that because of the aberration neither the Baum spot (in the original WFC) nor the high-resolution coronograph on the FOC (Paresce et al. 1990), designed to tackle QSO hosts, are now available. Things will improve with the coronographic facility on NICMOS (Axon et al. 1995), but we believe that a still higher resolution coronograph should be urgently considered for future refurbishment missions.

P. J. B. acknowledges financial support from the Particle Physics and Astronomy Research Council.

REFERENCES

Armus, L., Surace, J. A., Soifer, B. T., Matthews, K., Graham, J. R., & Larkin, J. E. 1994, AJ, 108, 76
Axon, D. J., et al. 1995, NICMOS Instrument Handbook (Baltimore: STSCI)
Bahcall, J. N., Kirhakos, S., & Schneider, D. F. 1994, ApJ, 435, L11
———. 1995a, ApJ, 447, L1
———. 1995b, ApJ, 450, 486
———. 1996, ApJ, 457, 557
Carico, D. P., Graham, J. R., Matthews, K., Wilson, T. D., Soifer, B. T., Neugebauer, G., & Sanders, D. B. 1990, ApJ, 349, L39
Disney, M. J., et al. 1995, Nature, 376, 150
Hamilton, D., & Keel, W. C. 1987, ApJ, 321, 211
Hutchings, J. B., Holtzman, J., Sparks, W. B., Morris, S. C., Hanisch, R. T., & Mo, J. 1994, ApJ, 429, L1
Hutchings, J. B., & Morris, S. C. 1995, AJ, 109, 1541
Hutchings, J. B., & Neff, S. G. 1988, AJ, 96, 1575
———. 1991, AJ, 101, 434
Krist, J. 1993, in ASP Conf Ser., Vol. 52, Astronomical Data Analysis Software and Systems II, ed.R. J. Hanish, R. J. V. Brissenden, & J. Barnes (San Francisco: ASP), 530
Krist, J., & Burrows, C. 1994, WFPC2 Instrument Sci. Rep. 94-01
Lipari, S., Colina, L., & Macchetto, F. 1994, ApJ, 427, 174
Low, F. J., Cutri, R. M., Kleinman, S. G., & Huchra, J. P. 1989, ApJ, 340, L1
Low, F. J., Huchra, J. P., Kleinman, S. G., & Cutri, R. M. 1988, ApJ, 327, L41
Lynds, C. R., & Toomre, A. 1976, ApJ, 209, 382
Majewski, S. R., Hereld, M., Koo, D. C., Illingworth, G. D., & Heckman, T. M. 1993, ApJ, 402, 125
McLeod, K. K., & Rieke, G. H. 1995, ApJ, 454, L77
Paresce, F., et al. 1990, Faint Object Camera Instrument Handbook (Baltimore: STSci)
Sanders, D. B., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N.Z. 1988, ApJ, 325, 74
Trauger, J.T., et al. 1994, ApJ, 435, L3
Veron-Cetty, M. P., & Veron, P. 1993, ESO Sci. Rep., No. 13, A Catalogue of Quasars and Active Nuclei (6th ed.; Garching: ESO)

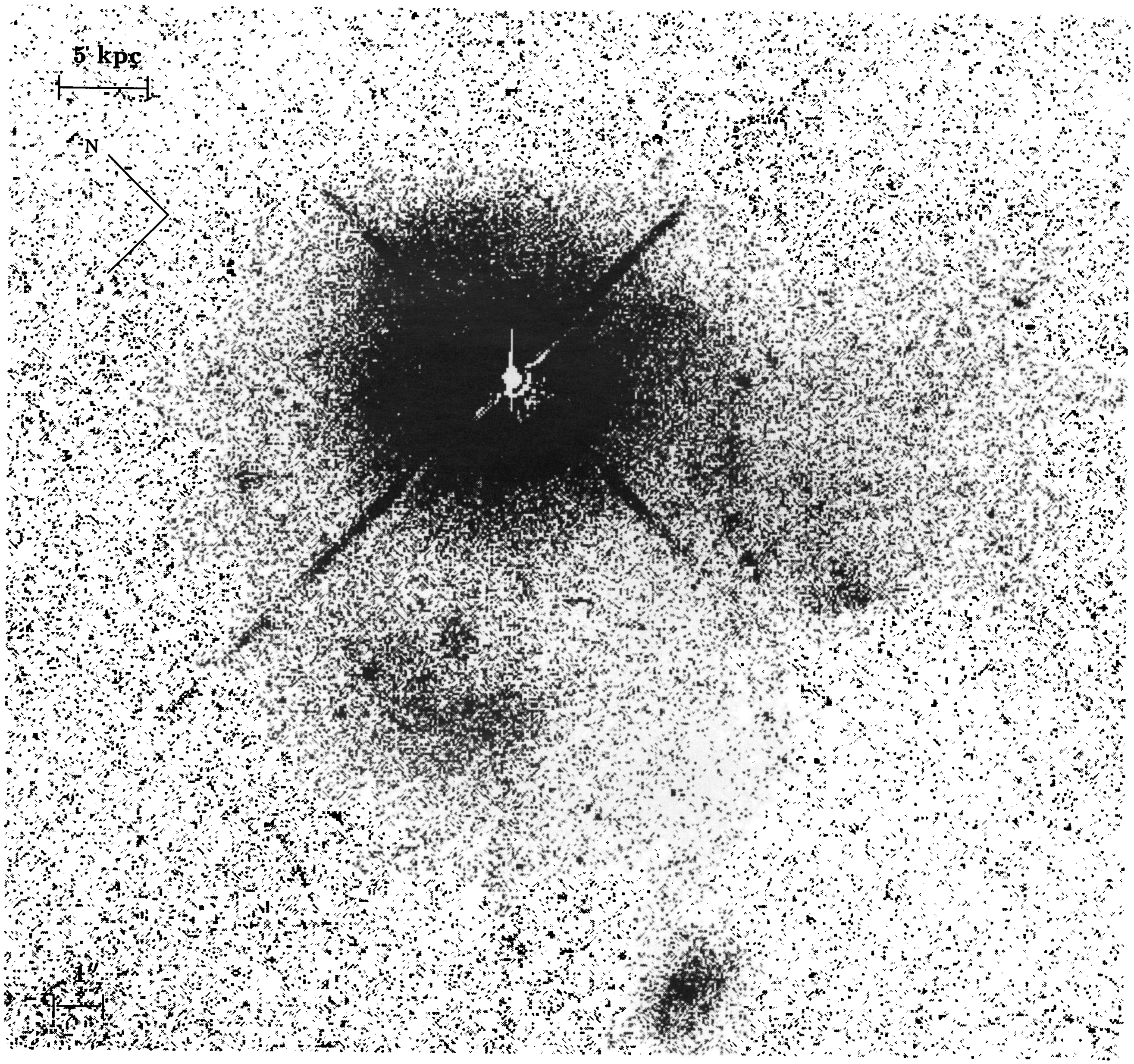

FIG. 4.—PC image of IRAS 07598+6508

BOYCE et al. (see 473, 762)