THE ASTROPHYSICAL JOURNAL, 329: L75–L79, 1988 June 15

2.2 MICRON IMAGE OF 3C 368 AT $z = 1.13$, A GALAXY WITH ALIGNED RADIO AND STELLAR AXES

K. C. CHAMBERS[1,2]
Center for Astrophysical Sciences, Department of Physics and Astronomy, The Johns Hopkins University
G. K. MILEY[1,2,3,4,5]
Space Telescope Science Institute
AND
R. R. JOYCE
National Optical Astronomy Observatories
Received 1987 December 14; accepted 1988 March 17

ABSTRACT

We present a K-band infrared image of the $z = 1.13$ radio galaxy 3C 368. This galaxy is one of the brightest examples of the recently discovered phenomenon of alignment between the optical and radio axes of powerful distant radio galaxies. Our observations show that the infrared morphology is also elongated and aligned along the optical and radio axes. However, it is not coincident with the radio emission. We discuss various mechanisms for producing the infrared and optical flux, and the resultant constraints on the origin of the alignment effect in high-redshift radio galaxies. The most likely explanation is that the emission is produced mainly by young stars formed by interaction of the radio source with the interstellar medium. The infrared flux is then interpreted as dominated by a population of red supergiants. Independent of the origin of the emission, the observed alignment implies that powerful radio galaxies at high redshifts are distinct from giant ellipticals, even in the infrared. Hence, attempts to derive a cosmological "standard candle" using studies which combine these two types of galaxies are likely to be invalid.

Subject headings: cosmology — galaxies: evolution — galaxies: redshifts — galaxies: stellar content — infrared: general — radio sources: galaxies

I. INTRODUCTION

Galaxies associated with powerful radio sources are among the most frequently used cosmological probes because their enormous radio luminosities enable them to be pinpointed easily out to large distances. Traditionally it was assumed that radio galaxies are giant ellipticals, but during the last few years evidence has mounted that counterparts of the most powerful radio sources at low redshifts ($z < 0.5$) have peculiar optical morphologies (e.g., Heckman *et al.* 1986) and far-infrared (60 μm) excesses (Golombek, Miley, and Neugebauer 1988) compared with normal ellipticals. Optical images of high-redshift radio galaxies are also known to be peculiar; they are often elongated and even multimodal (Spinrad 1986; Lilly and Longair 1984). However, the most surprising property of powerful high-redshift radio galaxies is provided by the recent discovery that their optical extensions tend to be aligned with the axes of their associated radio sources (Chambers, Miley, and van Breugel 1987; McCarthy *et al.* 1987; Chambers, Miley, and van Breugel 1988). In this they differ from radio galaxies at low redshifts.

Several possibilities have been proposed to explain the alignment effect. One of the most crucial diagnostics in discriminating between the various alternatives is to examine the spectral energy distribution of the extended emission across the widest possible spectral range. The near-infrared region is particularly important in this regard. As one of the brightest examples of the radio-optical alignment, 3C 368 is a prime candidate for infrared imaging.

II. OBSERVATIONS AND DATA

The KPNO IR imager utilizes a 58 × 62 InSb focal plane array manufactured by Santa Barbara Research Corporation. The design and operation is described in Orias, Hoffman, and Casselman (1986) and Fowler *et al.* (1987). Our observations were made on 1987 October 3, under mediocre seeing conditions (~1″.3 FWHM), with the array at the f/15 Cassegrain focus (0″.75 pixels) of the KPNO 2.1 m telescope. The galaxy was imaged successively at three different positions on the chip, 16 times each for 80 s, to facilitate background removal. The images were reduced using IRAF, the NOAO image processing software package. Image processing consisted of flat-fielding, background subtraction, and registration of the individual frames. Because of problems with flat-fielding, not all the data taken were included in the final image. Figure 1*a* shows the resultant contour diagram of the final K-band image. The relative scale was determined from images of fields with stars whose angular separations were measured on the Palomar Sky Survey. The image scale is accurate to ±2%. The absolute positioning was determined by offsetting the telescope from a nearby star whose position had been accurately (<0″.5) measured on the Sky Survey. Using this procedure the absolute astrometric errors should be less than 1″.

[1] Visiting Astronomer, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
[2] Visiting Astronomer, National Radio Astronomy Observatories, operated by Associated Universities Inc., under contract with the National Science Foundation.
[3] Affiliated to Astrophysics Division, Space Science Department, ESA, Noordwijk, The Netherlands.
[4] On leave from Sterrewacht, Leiden, The Netherlands.
[5] Research Professor, The Johns Hopkins University.

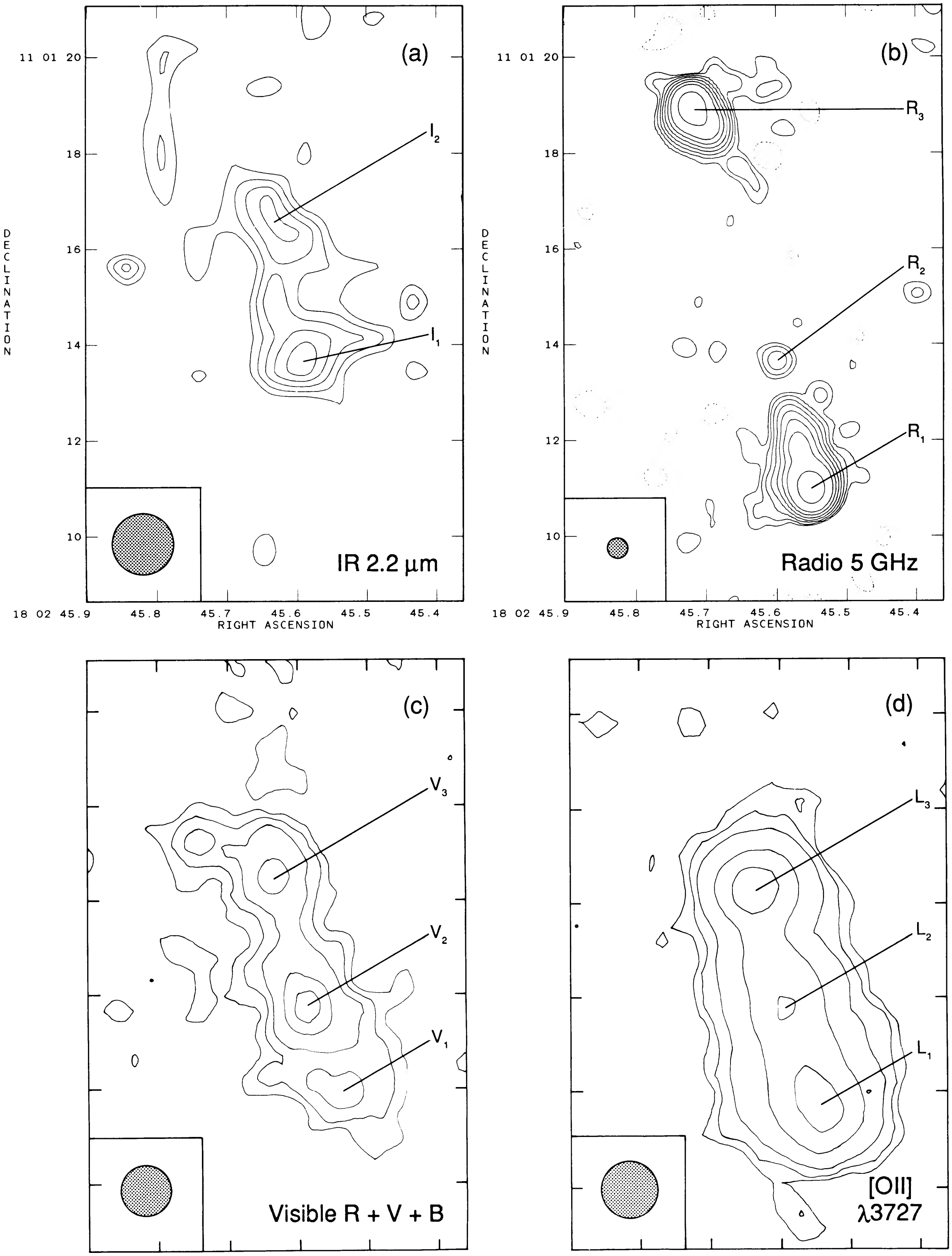

FIG. 1.—Images of 3C 368 at the same scale and positioned to within < 1″.0. (*a*) 2.2 μm image. Contours are 30, 45, 60, 75, and 90% of peak flux. (*b*) VLA radio intensity image made at 4885 MHz in the A-array. Contour levels are 0.4 mJy × (−2, 2, 4, 8, 16, 32, 64, 128, 512). (*c*) Sum of continuum (*BVR*) images. Contour levels are 8, 15, 25, 50, and 80% peak intensity; from Djorgovski *et al.* (1987). (*d*) Interference filter image centered on the redshifted [O II] λ3727 line. Contour levels are at 5, 10, 20, 50, and 80% of peak intensity; from Djorgovski *et al.* (1987). The various positions are delineated on the figures. We associate the position I_1 with R_2, V_2, and L_2; and the position I_2 with V_3 and L_3.

The integrated magnitude of the galaxy was determined by measuring the difference between the total integrated flux in a synthetic rectangular $5'' \times 8''$ aperture placed over the image of the galaxy and the average background from surrounding areas. The array was flux-calibrated relative to the standard stars HD 162208 and HD 44162, assuming the magnitudes determined by Elias *et al.* (1982) and correcting differentially for atmospheric extinction. The galactic extinction was derived using $E_{B-V} = 0.16$ (Burstein and Heiles 1982) and assuming the same value of A_K/A_V as Frogel *et al.* (1978). These corrections are less than 0.08 mag. The result is an integrated K magnitude of 16.85 ± 0.2, in agreement to within the errors with the value of 16.88 ± 0.16 obtained by Lilly and Longair (1984) through a $10''.8$ aperture. At $z = 1.132$, the distance modulus is $(m - M) = 43.03$ and $1''$ corresponds to 8.4 kpc for a Friedmann cosmology with $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$. Using these values and a K-correction estimated from our spectral energy distribution of 3C 368, and making no correction for evolution, the absolute magnitudes are $M_V = -24.4$ and $M_K = -26.4$.

In addition to the infrared image, Figure 1 shows radio, broad-band optical, and [O II] λ3727 images of 3C 368. The radio intensity map was made at 4885 MHz with the VLA in the A-configuration (Chambers and Miley 1988). The optical images are from Djorgovski *et al.* (1987). From Figure 1 it can be seen that the 2.2 μm emission is distinctly bimodal and extended. The maximum intensity at I_1 coincides with the optical maximum V_2 and the radio core R_2 to within the astrometric errors of $< 1''$. Identifying this with the nucleus, we find that the infrared image of the galaxy is extended toward the northeast at position angle $12° \pm 3°$, which is not significantly different from the radio orientation.

We do not detect any infrared emission from the region $V_1/L_1/R_1$. If this region has the same colors as the rest of the galaxy, its K-band flux would have been close to our detection limit.

III. DISCUSSION

The most striking result to follow from Figure 1 is that the 2.2 μm image of 3C 368 is aligned along the optical and radio axes of the galaxy. There is significant infrared flux extending at least 32 kpc from the radio core, spatially aligned along the radio axis, and located just inside the radio hot spots.

What implications does this result have for the origin of the optical/infrared light in 3C 368, and the various explanations given for the alignment effect (e.g., Chambers, Miley, and van Breugel 1987)? There are several possibilities:

1. 3C 368 is not a typical case, and the alignment observed here is fortuitous. We chose 3C 368 for infrared imaging because it was one of the brightest galaxies in the samples of Chambers, Miley, and van Breugel (1987) and McCarthy *et al.* (1987), as well as having one of the best defined optical axes. There is no reason to doubt that the alignment of the infrared flux observed in 3C 368 is due to similar processes that produce the optical alignment in other powerful radio galaxies at high redshift.

2. The observed alignment is due to a statistical bias caused by enhancement of the radio emission when the jet happens to be oriented along the stellar axis. Although there is mounting evidence that interaction with matter is an important method of making jets radiate at radio frequencies, the alignment effect is observed only for powerful radio sources at high redshifts. One would expect that such a statistical bias would produce an observable effect at lower redshifts, but this is not seen (Chambers, Miley, and van Breugel 1987; McCarthy *et al.* 1987; and references therein). Furthermore, the unusual optical/IR morphologies would require an independent explanation.

3. The broad-band emission is dominated by emission lines from an ionized gas with which the radio source is interacting. Figure 1*d* from Djorgovski *et al.* (1987) shows the extent of the [O II] λ3727 emission in 3C 368. It is clearly elongated along the radio axis, and even spatially coincides with the southern radio lobe. It is likely that the broad-band R image is slightly contaminated by the redshifted [O II] λ3727 emission. Similarly the J-band measurement may be affected by a large Hα + [N II] flux. But there are no strong redshifted emission lines that fall into the K band that could distort our 2.2 μm image. Hence, we can rule out the extended line emission as producing the observed infrared morphology.

4. The optical/infrared/radio emission is enhanced by a gravitational lens formed by a foreground galaxy. Le Fevre *et al.* (1987) have suggested that the optical elongation of 3C 324 was caused by such an effect. Our high-resolution radio map shows a typical edge-brightened morphology and no evidence of a lensed radio core (Fig. 1*b*). Given the correlation between radio spectral index and radio luminosity (e.g., Blumenthal and Miley 1979), the fact that 3C 368 has an ultrasteep radio spectrum ($\alpha = -1.3$) is consistent with its having a high radio luminosity and being among the most distant radio galaxies in the 3CR sample. Furthermore, long-slit spectra of Djorgovski *et al.* (1987) show spatial variations in the velocities and velocity widths in at least two spectral lines. This can not be accounted for by a gravitational lens.

5. The infrared and optical morphologies are dominated by nonthermal emission related to the radio source. This is unlikely because of the lack of spatial coincidence between the radio and infrared emission. A simple extrapolation of the radio synchrotron spectrum using the radio flux limits at the location of the infrared emission underestimates the optical infrared fluxes by more than four orders of magnitude. We therefore discount the possibility that we are seeing the high-frequency tail of the radio synchrotron emission.

Nonthermal IR/optical emission can also be produced by inverse Compton scattering of the microwave background radiation by the radio emitting relativistic plasma. If the I_2/V_3 region were to contain a "low-frequency bridge" emitting radio emission with a 6 cm radio intensity below the detection limit of the present observations ($\sim$0.8 mJy per beam), and a similar spectral index as the observed IR/optical measurements ($\alpha = -1.7$), a magnetic field strength of $\sim 10^{-7}$ G would be needed in order to produce the observed IR/optical flux (e.g., Felton and Morrison 1966; Saslaw, Tyson, and Crane 1978; Miley 1980). This is a factor of $\sim 10^3$ smaller than the corresponding equipartition value. Deviation from equipartition by such a large amount would be surprising. However, anisotropy, beaming, or any departure from simple geometry would affect the derived parameters. Given the absence of observed radio emission from I_2/V_3 and the departure from equipartition required to produce the observed flux, we are reluctant to advocate a nonthermal explanation. However, the sensitivity of the inverse Compton effect to the energy spectrum of the relativistic electrons and the redshift (background radiation energy density) would provide a natural explanation for the fact that the alignment effect only appears to be present in distant radio galaxies whose radio spectra tend to be steep (Chambers, Miley, and van Breugel 1987).

6. The likeliest interpretation is that the infrared/optical flux

is starlight. Such an interpretation for the alignment effect requires the existence of a relationship between the stellar emission and the radio activity. Any such relationship must call into question the common assumptions that powerful radio galaxies at high redshift are less evolved versions of normal giant elliptical galaxies.

The natural candidates for producing the infrared emission are then an old ($\sim 10^9$ yr) population of red giants, as appears to be the case for low-redshift radio galaxies, or a relatively young ($\sim 10^7$ yr) population of red supergiants. The minimum mass required to explain the observed infrared emission differs considerably according to these two interpretations. For example, taking a K5 III red giant to have $M_V = -0.2$ (Allen 1973) and $V-K = 3.67$ (Koorneef 1983), it would require $\sim 10^9$ red giants with $\sim 5 \times 10^9\ M_\odot$ to account for the infrared flux in region I_2 from the red giants alone. On the other hand, taking a K5 Ia supergiant to have $M_V = -7.5$ (Allen 1973) and $V-K = 3.7$ (Koorneef 1983), then the infrared flux could be accounted for by only $\sim 6 \times 10^5$ red supergiants or $\sim 10^7\ M_\odot$. Of course both in the case of giants or supergiants, the total mass of all stars involved will depend on the IMF but will be orders of magnitude larger than the values quoted here (e.g., Scoville and Norman 1988).

According to the conventional interpretation of high-redshift radio galaxies as less evolved giant ellipticals, the spectral energy distributions have been interpreted as being dominated in the infrared by a population of red giants, and in the optical and ultraviolet by young stars due to ongoing bursts of star-formation (Lilly and Longair 1984). Such an interpretation of the infrared emission in our K-band image would require that the regions I_1 and I_2 have the equivalent stellar content of two extremely large giant ellipticals. It is difficult to reconcile such large masses and stellar ages with the observed alignment between the radio and stellar axes. There is no obvious reason why a merger would preferentially occur along the radio axis. One can speculate that a preferred direction is seeded primordially during the production of the radio sources and the formation of their associated galaxies. But how can such a structure be maintained for $\geq 10^9$ yr?

On the other hand, if, as suggested by Chambers, Miley, and van Breugel (1987) and McCarthy *et al.* (1987) vigorous star formation is caused by the interaction of the radio jet with its environment, the light may be dominated by relatively young massive stars. Although it is not a general phenomenon, there is evidence that jet-induced star formation does indeed occur in low-redshift objects such as Minkowski's object (van Breugel *et al.* 1985; Brodie, Bowyer, and McCarthy 1985).

The red supergiant explanation would imply that powerful distant radio galaxies have an unconventional initial mass function (IMF), which is strongly biased against the formation of solar-mass stars as compared with the solar neighborhood. Rieke *et al.* (1980) have shown that this is likely to be the case for the nuclear regions of M82 and NGC 253, where the observed strong CO absorption bands and the inferred mass-to-infrared-light ratio requires that more than 15% of the infrared flux is produced by red supergiants. Moreover, Wyse and Silk (1987) have shown that the optical colors of high-redshift galaxies are consistent with bimodal models of the IMF which favor the formation of massive stars.

As to how such an IMF might arise, Larson (1977) has proposed that the formation of low-mass stars could be suppressed in active galactic nuclei, because less massive clouds do not have sufficient self-gravity to overcome the forces resisting contraction, such as turbulence from supernovae, tidal effects, and large magnetic fields. For jet-induced star formation in powerful radio galaxies like 3C 368, a strong bias against low-mass stars could similarly be accounted for by the turbulence and magnetic fields in the cocoons of radio jets (Norman *et al.* 1982). However, it is unclear whether such processes could trigger the formation of such enormous numbers of stars ($\geq 10^9\ M_\odot$).

IV. CONCLUSION

Although we favor a stellar interpretation, we cannot rule out an inverse Compton origin for the optical and infrared emission in 3C 368. Since the detection of a steep spectrum radio bridge coincident with the IR/optical components would be evidence in favor of this latter explanation, more sensitive studies of 3C 368 at low frequencies are desirable.

Assuming that the infrared/optical emission is indeed starlight, our K-band image demonstrates that the region aligned with the radio axis must include not only main-sequence stars, but also stars in the red giant/supergiant phase. The crucial question is whether the infrared flux is dominated by evolved red giant stars or a relatively young population of red supergiants. Although we have argued that the evidence favors the supergiants, further observations of objects like 3C 368 are essential to resolve these questions unambiguously. Perhaps the most conclusive observation would be detection of strong CO absorption bands at a rest wavelength of $\sim 2.35\ \mu$m produced by an extreme population of late-type red supergiants (Rieke *et al.* 1980; Johnson and Mendez 1970). If the infrared flux of distant radio galaxies is indeed dominated by emission from red supergiants, there might well be other consequences for the spectral energy distributions. In particular, red supergiants have 4000 Å breaks which are as strong as or stronger than those of red giants which dominate giant ellipticals (e.g., Hamilton 1985) and low-redshift radio galaxies (Spinrad 1986). Differences in the strengths of the 4000 Å break between powerful radio galaxies and radio-quiet ellipticals at high redshift could contribute to differences in their broad-band IR/optical colors. Therefore detailed infrared spectroscopic study of the 4000 Å break for the highest redshift radio galaxies is desirable.

Finally, we caution against using powerful radio galaxies as cosmological probes or tests of conventional models of galaxy evolution. Observational evidence that stellar populations in galaxies evolve is based mainly on high-redshift radio galaxies such as 3C 368. The alignment effect demonstrates that there is a component present in the optical and infrared emission of high-redshift radio galaxies associated with the radio activity which is not present in low-redshift radio galaxies. This component is superimposed on any "normal" galaxy emission independent of its origin (e.g., jet-induced star formation, or inverse Compton emission). Hence, even if the observed emission is stellar, the radio selection bias and unknown star formation mechanisms suggest that conventional models of evolving stellar populations assuming normal IMFs (e.g., Bruzual 1983; Chokshi and Wright 1987) are probably irrelevant for objects like 3C 368. For these reasons we suggest that until the alignment effect is better understood, high-redshift radio galaxies should not be combined with giant ellipticals and low-redshift radio galaxies as infrared/optical "standard candles." Nor should they be used as general "test-beds" for modeling the evolution of normal galaxies.

These observations would have been impossible except for the help and expertise of the KPNO technical and engineering staff. We are grateful to them and the Director of KPNO for making the array available to us and to the staffs of KPNO and the VLA for their assistance with the observations. Jeannette Barnes and Francisco Valdes provided invaluable assistance with IRAF. It is a pleasure to thank S. (George) Djorgovski and his collaborators for kindly allowing us to reproduce their optical data in Figures 1*c* and 1*d*. Finally we enjoyed stimulating discussions with R. (Ski) Antonucci, George Blumenthal, Ron Ekers, Tim Heckman, David Koo, Jan Koornneef, Peter Quinn, and Rosie Wyse. We are particularly indebted to Hy Spinrad whose comments improved the manuscript considerably. K. C. C. thanks Arthur Davidsen and acknowledges support from the Hopkins Ultraviolet Telescope Project, NASA contract NAS 5-27000, and the hospitality of the Space Telescope Science Institute.

REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (3d ed.; London: Athlone Press).
Blumenthal, G., and Miley, G. 1979, *Astr. Ap.*, **80**, 13.
Brodie, J., Bowyer, S., and McCarthy, P. 1985, *Ap. J. (Letters)*, **293**, L59.
Bruzual, A. G. 1983, *Ap. J.*, **273**, 105.
Burstein, D., and Heiles, C. 1982, *A.J.*, **87**, 1165.
Chambers, K. C., Miley, G. K., and van Breugel, W. 1987, *Nature*, **329**, 604.
———. 1988, *Ap. J. (Letters)*, **327**, L47.
Chambers, K. C., and Miley, G. K. 1988, in preparation.
Chokshi, A., and Wright, E. L. 1987, *Ap. J.*, **319**, 44.
Djorgovski, S., Spinrad, H., Pedelty, J., Rudnick, L., and Stockton, A. 1987, *A.J.*, **93**, 1307.
Elias, J. H., Frogel, J. A., Matthews, K., and Neugebauer, G. 1982, *A.J.*, **87**, 1029.
Felton, J. E., and Morrison, P. 1966, *A.J.*, **146**, 686.
Frogel, J. A., Persson, S. E., Aaronson, M., and Matthews, K. 1978, *Ap. J.*, **220**, 75.
Fowler, A. M., Probst, R. G., Brit, J. P., Joyce, R. R., and Gillett, F. C. 1987, *Opt. Eng.*, **26**, 232.
Golombek, D. A., Miley, G., K., and Neugebauer, G. 1988, *A.J.*, **92**, 26.
Hamilton, D. 1985, *Ap. J.*, **297**, 371.
Heckman, T. M., Smith, E. P., Baum, S. A., van Breugel, W. J. M., Miley, G. K., Illingworth, G. D., Bothun, G. D., and Balick, B. 1986, *Ap. J.*, **311**, 526.
Johnson, H. L., and Mendez, M. E. 1970, *A.J.*, **75**, 785.
Koorneef, J. 1983, *Astr. Ap.*, **128**, 84.
Larson, R. B. 1977, in *The Evolution of Galaxies and Stellar Populations*, ed. B. M. Tinsley and R. B. Larson (New Haven: Yale Observatory), p. 97.
Le Fevre, O., Hammer, F., Nottale, L., and Mathez, G. 1987, *Nature*, **326**, 268.
Lilly, S. J., and Longair, M. S. 1984, *M.N.R.A.S.*, **211**, 833.
McCarthy, P. J., van Breugel, W., Spinrad, H., and Djorgovski, S. 1987, *Ap. J. (Letters)*, **321**, L29.
Miley, G. K. 1980, *Ann. Rev. Astr. Ap.*, **18**, 165.
Norman, M. L., Smarr, L., Winkler, K. H., and Smith, M. D. 1982, *Astr. Ap.*, **113**, 285.
Orias, G., Hoffman, A. W., and Casselman, M. F. 1986, *Proc. SPIE*, **627**, 408.
Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., and Tokunaga, A. T. 1980, *Ap. J.*, **238**, 24.
Saslaw, W. C., Tyson, J. A., and Crane, P. 1978, *A.J.*, **222**, 435.
Scoville, N., and Norman, C. 1988, in preparation.
Spinrad, H. 1986, *Pub. A.S.P.*, **98**, 269.
van Breugel, W., Filippenko, A., Heckman, T., and Miley, G. 1985, *Ap. J.*, **293**, 83.
Wyse, R. F. G., and Silk, J. 1987, *Ap. J. (Letters)*, **319**, L1.

K. C. Chambers: Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218

R. R. Joyce: National Optical Astronomy Observatories, 950 North Cherry Avenue, Tucson, AZ 85726

G. K. Miley: Space Telescope Science Institute, 3800 San Martin Drive, Baltimore, MD 21218