THE ASTROPHYSICAL JOURNAL, 314:L33–L37, 1987 March 15

EMISSION-LINE GALAXIES IN THE BOOTES VOID

J. WARD MOODY[1]
Institute for Astrophysics, The University of New Mexico
ROBERT P. KIRSHNER[1]
Harvard-Smithsonian Center for Astrophysics
GORDON M. MACALPINE[1]
Department of Astronomy, The University of Michigan
AND
STEPHEN A. GREGORY
Institute for Astrophysics, The University of New Mexico
Received 1986 November 12; accepted 1986 December 22

ABSTRACT

Redshifts for emission-line galaxies found in an objective prism search of the Bootes void place three new galaxies inside the void. This brings the number of known galaxies in the void to eight, all of which were detected because of line emission. Most of the galaxies are on the order of $10h^{-1}$ kpc in diameter and exhibit irregular morphologies. Spectroscopically, they resemble H II regions with narrow lines and moderately weak stellar continua. The exceptions are I Zw 81 which has a well-defined nucleus and Mrk 845 which is a Seyfert 1 spiral. The presence of some emission-line galaxies shows that the void is not completely empty, despite being a conspicuous feature in magnitude-limited surveys. The presence of these galaxies is consistent with a void density of one-tenth that of the mean, assuming that the proportion of emission-line galaxies is the same as in field samples. Another possibility is that the void density is lower, consistent with the result from the magnitude-limited samples, and the fraction of galaxies with emission lines is correspondingly higher.

Subject headings: galaxies: clustering — galaxies: redshifts

I. INTRODUCTION

Extensive galaxy redshift surveys reveal large volumes with very low density (Tifft and Gregory 1976; Gregory and Thompson 1978; Tarenghi *et al.* 1979; Einasto, Joeveer, and Saar 1980; Davis *et al.* 1982; de Lapparent, Geller, and Huchra 1986). A particularly interesting void is the very large (10^6 Mpc^3) void in a survey of field galaxies in the direction of Bootes (Kirshner *et al.* 1981, 1983*a*, *b*, 1987, hereafter respectively KOSS 81, KOSS 83*a*, KOSS 83*b*, KOSS 87). These regions are only known to be missing relatively bright galaxies. One key question is whether they lack mass or only bright galaxies? Aside from hypothetical weakly interacting particles, or other hard-to-observe forms of mass, might they contain a population of dwarf, low surface brightness, or peculiar galaxies? This *Letter* reports the results of a search for emission-line galaxies in the Bootes void.

After the discovery of the Bootes void, Balzano and Weedman (1982) suggested that Markarian galaxies follow a uniform distribution in this area of the sky and show no void. Moody (1986) showed that because Balzano and Weedman used such a large area, and because the Markarian survey is too shallow to survey the void well, the Bootes void would not be expected to create a significant gap in their velocity histogram. However, their work did call attention to the fact that one Markarian galaxy, Mrk 845, is within the Bootes void. Sanduleak and Pesch (1982) searched for fainter emission-line galaxies (ELGs) in the southern portion of the void. Redshifts of these Case galaxies (CG) obtained by Tifft *et al.* (1986) show two of them are within the void boundaries. In addition KOSS 87 point out that a redshift from Sargent (1970) places I Zw 81 in the void. An eighth emission-line galaxy, CG 1432+53 has recently been reported by Weistrop and Downes (1987). It is at the very edge of the void, and it is included in the discussion, but not the observations reported in this *Letter*.

Following the discovery of the Bootes void we began to search its center for ELGs. The complete results of this survey will be given in Moody, MacAlpine, and Kirshner (1987). Here, in § II, we briefly discuss our search technique and report three more galaxies within the void. In § III we examine the properties of these objects and their relation to the Bootes void. In § IV we summarize our results and briefly consider their implications.

[1] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, under contract with the National Science Foundation; observations made with the Burrell Schmidt of the Warner and Swazey Observatory, Case Western Reserve University.

TABLE 1

EMISSION-LINE GALAXIES IN THE BOOTES VOID

Object	α (1950)	δ (1950)	cz (km s^{-1})	Void Distance (km s^{-1})	EW (5007)	5007/(Hβ)	m	M	Dh^{-1}	Description	Reference
I Zw 81	$14^h06^m24^s$	+49°05′	15615	2174	...	3.1	16	−21	12	Round, well-centered nucleus	1, 2
CG 1432+53	14 32 48	53 02 18	13190	3070	...	...	16	−20.4	...	Not observed by us	3
MMK 1446+44	14 46 25	44 57 10	13196	2324	3	1.3	16.0	−20.4	6 × 10	Offset nucleus	4, 5
CG 1457+42	14 57 31	42 27 54	17380	2170	25	> 2	15.9	−21.1	9 × 15	Offset nucleus	6
Mrk 845	15 06 13	51 38 41	13810	2312	15	> 3	15.6	−20.8	11 × 32	Stellar nucleus; spiral	5, 7
MMK 1507+45	15 07 25	45 54 36	14658	1160	591	6	17.7	−18.9	< 2	Unresolved	4
MMK 1510+47	15 10 33	47 27 43	16059	1239	310	3	16.3	−20.4	8 × 10	Centered nucleus	5
CG 1517+39	15 17 56	39 56 27	14244	2406	51	1.4	16.2	−20.4	6 × 10	Offset nucleus; comet-like	5, 6

REFERENCES.—(1) Sargent 1970. (2) Koski 1978. (3) Weistrop and Downes 1987. (4) Moody 1986. (5) This *Letter*. (6) Tifft *et al.* 1986. (7) Osterbrock and Dahari 1983.

II. OBSERVATIONS

a) *Survey Technique*

We searched the heart of the Bootes void using the Burrell Schmidt with the 4°5 UV prism, IIIa-F emulsion, and an interference filter with a 4600–5500 Å bandpass. This combination provides a reciprocal dispersion of 900 Å mm^{-1} at Hβ, allows for detection of the 5007 line out to a redshift of $z = 0.1$, and enables long exposures since 5577 Å night sky emission is filtered out. This technique was chosen over the more common 1°8 apex prism and IIIa-J emulsion surveys (Smith 1975; MacAlpine, Smith, and Lewis 1977; Sanduleak and Pesch 1982, 1987) to avoid problems in detecting the [O III] 5007, 4959 blend at the redshift of the Bootes void ($0.04 < z < 0.06$). Problems arise from compression of the continuum near the emulsion red limit which tends to mask the presence of emission.

All of our exposures were 3 hr giving a limiting magnitude of approximately 18 in the Gunn g band. The survey consists of 12 plates covering 210 deg^2, centered at $\alpha = 14^h\ 50^m$, $\delta = +47°$. The plates were searched with a stereo microscope at a magnification of 15x. One hundred and ten candidates with one or more possible emission lines were selected.

b) *Medium-Dispersion Spectra*

Spectra have been obtained for 79 of the 110 candidates using the MMT, Whipple Observatory 1.5 m, NOAO 2.1 and the McGraw Hill 1.3 m telescopes with resolutions of order 5–7 Å.

Table 1 presents the three newly discovered void objects, MMK 1446+44, MMK 1507+45, and MMK 1510+47, together with the five objects drawn from our previous work and the literature. Our redshifts were measured from prominent, unblended emission lines and corrected to the local frame by $v = 300 \sin l \cos b$. Where two references are given, the listed value is the mean of the two measurements. The table also gives the distance in velocity units from the object to the void center, which is at $\alpha = 14^h 50^m$, $\delta = +46°$, and $cz = 15{,}500$ with a radius of 3100 km s^{-1} (KOSS 83*a*). There is a broad range of emission strengths. The [O III] 5007 equivalent widths range from about 600 Å to only 3 Å in the case of MMK 1446+44. Spectra for Mrk 845 and the MMK and Case galaxies are presented in Figures 1*a*–1*f*.

c) *CCD Images*

We obtained direct images of seven void galaxies using the University of New Mexico Capilla Peak Observatory 0.6 m telescope and Photometrics RCA CCD camera which gives a scale of 0″7 pixel^{-1}. For five galaxies we have 15 minute exposures through a Mould R filter under nonphotometric conditions. For two objects, MMK 1446+44 and Mrk 845, we have unfiltered 10 minute exposures. Figures 1*a*–1*f* also present isophotal maps of the galaxies. We have obtained photometric measures accurate to about 0.1 mag from additional observations with the McGraw-Hill 1.3 m telescope and the MASCOT CCD (Ricker *et al.* 1981).

Morphological properties of these galaxies are also given in Table 1. The minimum and maximum diameters listed refer to a 23.1 mag arcsec^{-2} isophote in the R frames or a level of 0.02 counts s^{-1} arcsec^{-2} above the sky for the unfiltered frames. The listed values were corrected for a 2″ seeing disk. The nonphotometric conditions make the estimated isophotal levels accurate to no better than 25%.

III. RESULTS

a) *Implications for the Bootes Void*

Figure 2 presents a map of the Bootes void region showing the location of the eight galaxies with respect to the void. The galaxies are found well within the volume and are spread through it with no obvious clumping in redshift or position. The distances from the center of the void are given in Table 1. The closest to the void center, MMK 1507+45 is 1160 km s^{-1} away—the most distant is CG 1432+53, the object reported by Weistrop and Downes (1987) at about 3070

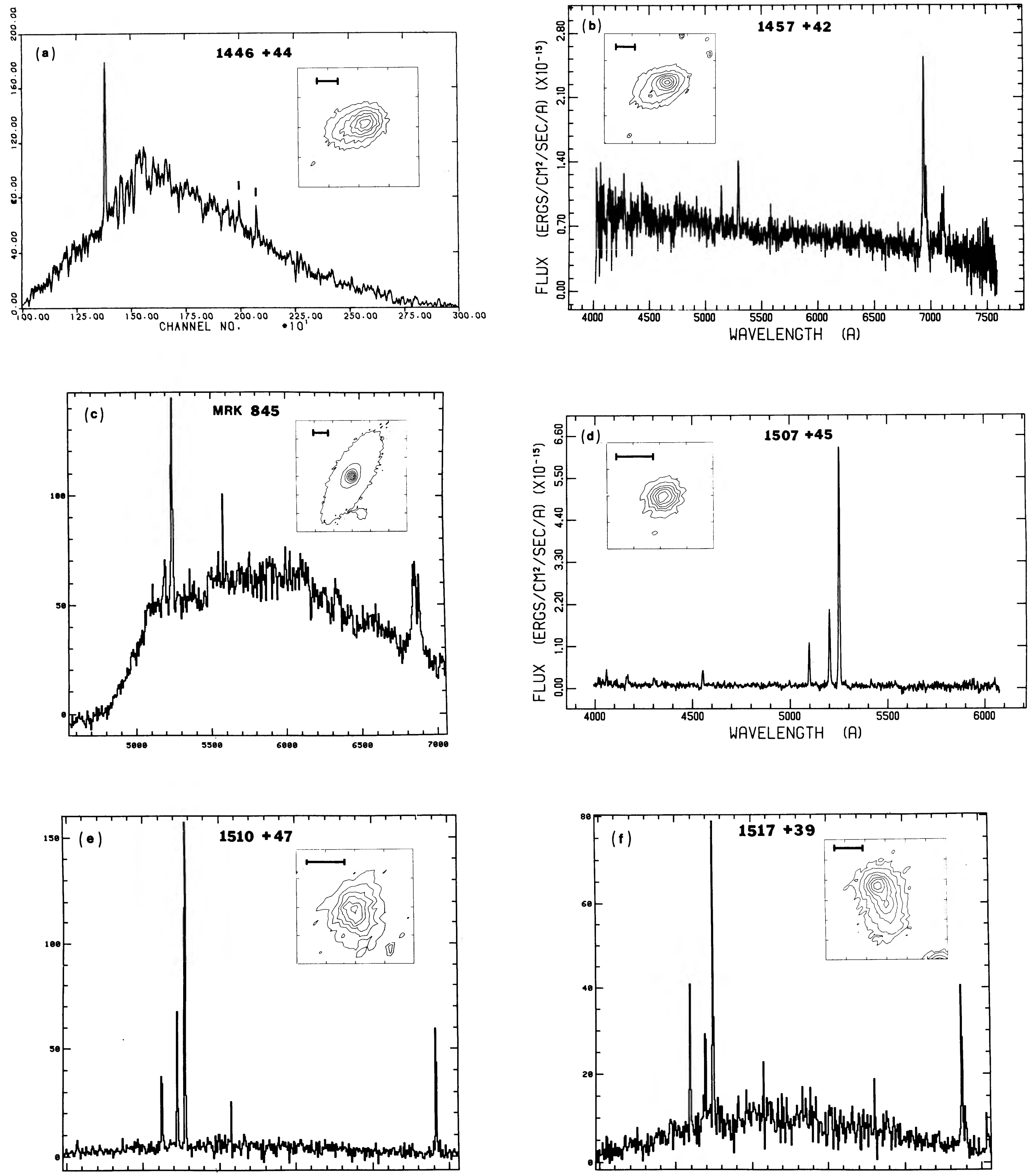

FIG. 1.—Unsmoothed spectra of void galaxies. Figs. 1*b* and 1*d* have been transformed to fluxes. Emission lines have been marked in (*a*) and confirmed by subsequent spectra. Inset are isophotal maps of the objects. North is up; east to the left. The bars are 5″ long. Isophotes are at 2, 8, 15, 30, 45, 60, 75, and 90% of the difference between the peak and the background.

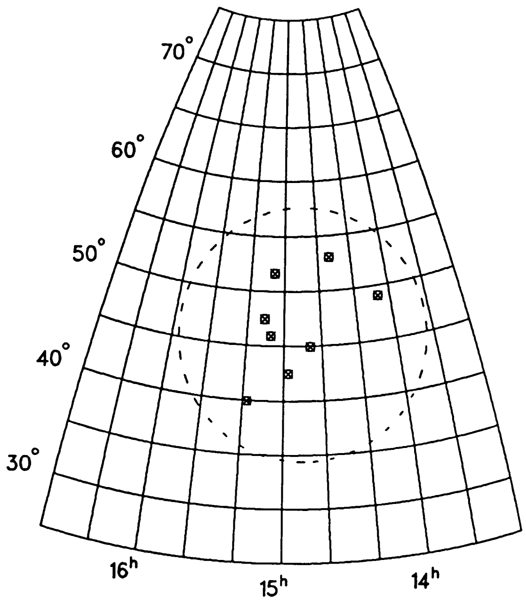

FIG. 2.—Equal area map showing the location of the eight galaxies. The dashed circle represents the projected boundary of the Bootes void.

km s^{-1} which is close to the 3100 km s^{-1} radius given by KOSS 83*a*.

The results of KOSS 87 show that none of their 239 galaxies lies within the void volume. They estimate that this volume has only a 1% chance of having a density greater than 0.25 of the cosmic mean. Yet we find that there are eight ELGs here. Are these facts consistent or do they require that the rare galaxies in the void are more likely to have emission than the general field population?

We note that seven of the eight galaxies within the void exhibit strong [O III] 5007 emission with equivalent widths greater than 10 Å. We do not have an exact value for I Zw 81. The description of the spectrum from Koski (1978) suggests that the emission is on the order of 10 Å. Only 5%–7% of the field has [O III] this strong (Dressler, Thompson, and Shectman 1985; Moody 1986). The KOSS survey covered 3% of the projected void area and would have found 31 galaxies in the void had there been a uniform distribution through it. This result suggests that the void lacks just over 1000 galaxies when compared with a uniform distribution. If void galaxies were no different from field galaxies, we would expect 50–70 ELGs with strong [O III] 5007 emission for a uniform distribution through the void. With this assumption the presence of eight strong emission-line galaxies here is consistent with a galaxy density depressed a factor of 10 below normal which agrees reasonably well with the upper limits given by KOSS 87. However, since neither our survey nor the Case surveys cover the entire void volume, this density estimate is only a lower limit, and the true density must be higher. Of course, any combination of space density of galaxies in the void and fraction of emission-line galaxies with a constant product will yield the same result. We consider it likely that the fraction of emission line galaxies is elevated in the void volume, as the best estimate of galaxy density from KOSS 87 is not their upper limit, but zero.

b) Galaxian Properties

The [O III] 5007/Hβ equivalent width ratio and permitted emission-line widths for seven of the eight galaxies are typical of galaxies with H II regions (Baldwin, Phillips, and Terlevich 1981). The exception is Mrk 845 which is classified a Seyfert 1 by Osterbrock and Dahari (1983). Although Sargent (1970) suspected that I Zw 81 (which he called I Zw 80) might be a Seyfert, Koski (1978) showed it is a normal galaxy with emission lines.

The morphologies of the galaxies are similar. Four of the six resolved objects, MMK 1446+44, CG 1457+42, MMK 1510+47, and CG 1517+39, are condensed and amorphous. They would probably be classified Irr II according to the precepts of Sandage (1961) since their surfaces are smooth. The brightest region in three of them is clearly offset from the center. The galaxy I Zw 81 is generally like these except it has an obvious, well-centered nucleus. The remaining object, Mrk 845, is a well-defined early-type spiral with a bright semistellar nucleus, which is typical of Seyferts, and a greater diameter of $32h^{-1}$ kpc.

These are objects of moderate size. The diameter of the largest, Markarian 845, is comparable to our Galaxy. Five of the objects are 50%–100% larger than M82. Their absolute magnitudes range from -21.1 to -18.9 in the g band (for $H_0 = 75$ km s^{-1} Mpc^{-1}). These values cluster near M_*, which is approximately -20.5 in g (KOSS 83*b*). These objects represent some of the most luminous galaxies in our survey. The distance to the Bootes void ($m - M = 36.6$) is such that we would be unlikely to have found any objects within it less luminous than these. Therefore, we do not rule out the possibility of fainter objects here, such as those reported by Salzer, MacAlpine, and Boroson (1986) in a void behind Virgo.

IV. DISCUSSION

We have shown that there are galaxies within the borders of the Bootes void as defined by KOSS 83*a*. All known galaxies within the Bootes void have emission line optical spectra and luminosities near M_*. Caution should be applied in interpreting these facts since emission was the criterion for discovery, and the magnitude limit of the survey implies a similar warning about the absolute magnitudes.

Melott *et al.* (1983) and Dekel and Silk (1986) have predicted the existence of late-forming low surface brightness dwarf galaxies in voids using cold dark matter models. However, the eight ELGs seen are significantly more luminous than the brightest dwarfs ($M_B < -18$) and do not have a low surface brightness. Bothun *et al.* (1986) have also found no tendency for redshift voids to be filled in by low surface brightness galaxies in a large sample of nearby ($z < 0.033$) galaxies.

The presence of these eight galaxies points out the need to improve the upper limit for *normal* galaxies in the void and for conducting a deeper, uniform prism survey. Thorough follow-up of the Case Survey (Sanduleak and Pesch 1987) would be a good first step. Large galaxy voids provide a stringent test for models of the formation of structure in the universe. Good limits on the density contrast, and detailed information on the few galaxies that have formed in the low-density region, are essential facts in building an accurate picture for galaxy formation and the origin of large-scale structure.

This work was supported by NSF grants AST 82-04215, AST 83-11414, and AST 85-20115.

REFERENCES

Baldwin, J. A., Phillips, M. M., and Terlevich, R. 1981, *Pub. A.S.P.* **93**, 5.
Balzano, V. A., and Weedman, D. A. 1982, *Ap. J. (Letters)*, **255**, L1.
Bothun, G. D., Beers, T. C., Mould, J. R., and Huchra, P. 1986, *Ap. J.*, **308**, 510.
Davis, M., Huchra, J., Latham, D. W., and Tonry, J. 1982, *Ap. J.*, **253**, 422.
Dekel, A., and Silk, J. 1986, *Ap. J.*, **303**, 39.
de Lapparent, V., Geller, M. J., and Huchra, J. P. 1986, *Ap. J. (Letters)*, **302**, L1.
Dressler, A., Thompson, I. B., and Shectman, S. A. 1985, *Ap. J.*, **288**, 481.
Einasto, J., Joeveer, M., and Saar, E. 1980, *M.N.R.A.S.*, **193**, 353.
Gregory, S. A., and Thompson, L. A. 1978, *Ap. J.*, **222**, 784.
Kirshner, R. P., Oemler, A., Jr., Schechter, P. L., and Shectman, S. A. 1981, *Ap. J. (Letters)*, **248**, L57 (KOSS 81).
______. 1983*a*, in *IAU Symposium 104, Early Evolution of the Universe and Its Present Structure*, ed. G. O. Abell and G. Chincarini (Dordrecht: Reidel), p. 197 (KOSS 83*a*).
______. 1983*b*, *A.J.*, **88**, 1285 (KOSS 83*b*).
______. 1987, *Ap. J.*, **314**, 493 (KOSS 87).
Koski, A. T. 1978, *Ap. J.*, **223**, 56.
MacAlpine, G. M., Smith, S. B., and Lewis, D. W. 1977, *Ap. J. Supplement*, **34**, 95.
Melott, A., Einasto, J., Saar, E., Suisalu, I., Klypin, A. A., and Shandarin, S. F. 1983, *Phys. Rev. (Letters)*, **51**, 935.
Moody, J. W. 1986, Ph.D. thesis, The University of Michigan.
Moody, J. W., MacAlpine, G. M., and Kirshner, R. P. 1987, in preparation.
Osterbrock, D. E., and Dahari, O. 1983, *Ap.J.*, **273**, 478.
Ricker, G. R., Bautz, M. W., Dewey, D., and Meyer, S. S. 1981, *Proc. Soc. Photo-Opt. Instr. Eng.*, **290**, 190.
Salzer, J. J., MacAlpine, G. M., and Boroson, T. A. 1986, *Bull. AAS*, **18**, 689.
Sandage, A. 1961, *The Hubble Atlas of Galaxies* (Washington: Carnegie Institution).
Sanduleak, N., and Pesch, P. 1982, *Ap. J. (Letters)*, **25**, L11.
______. 1987, *Ap. J. Suppl.*, in press.
Sargent, W. L. W. 1970, *Ap. J.*, **160**, 405.
Smith, M. G. 1975, *Ap. J.*, **202**, 591.
Tarenghi, M., Tifft, W. G., Chincarini, G., Rood, H. J., and Thompson, L. A. 1979, *Ap. J.*, **234**, 793.
Tifft, W. G., and Gregory, S. A. 1976, *Ap. J.*, **205**, 696.
Tifft, W. G., Kirshner, R. P., Gregory, S. A., and Moody, J. W. 1986, *Ap. J.*, **310**, 75.
Weistrop, D., and Downes, R. A. 1987, *Bull. AAS*, in press.

STEPHEN A. GREGORY and J. WARD MOODY: The Institute for Astrophysics, The University of New Mexico, Albuquerque, NM 87131

ROBERT P. KIRSHNER: Center for Astrophysics MS-19, 60 Garden Street, Cambridge, MA 02138

GORDON M. MACALPINE: Department of Astronomy, The University of Michigan, Ann Arbor, MI 48109-1090