Astron. Astrophys. 192, 90–94 (1988)

ASTRONOMY AND ASTROPHYSICS

Prediction of absorption line statistics for a network of quasars behind the Virgo cluster

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Received April 23, accepted September 21, 1987

Summary. The origin of the absorption features seen in the spectra of distant QSOs is still unresolved. We present predictions of the numbers and strengths of absorption lines expected for a network of QSOs behind the Virgo cluster based on the two distinct extrinsic hypotheses, *viz.* absorption by very extensive galactic halos or by very numerous low surface brightness dwarfs. The results are compared in order to see how the two hypotheses can be distinguished by currently feasible observations.

Key words: clusters: of galaxies: galaxies: general – haloes of: quasars: general

1. Introduction

It is apparent that selection effects in galaxy catalogues may seriously bias our view of the overall population of galaxies (Arp, 1965; Disney, 1976). In particular dwarf and/or low surface brightness galaxies are greatly under-represented and our knowledge of their true numbers is sketchy at best (see Bothun, 1986, for a recent review of the observational situation). If the effects of such biases are to be reduced, it is essential that information on the galaxy population should be obtained from as many types of observation as possible. One such candidate observation is that of absorption lines in the spectra of distant QSOs due to (presumed) intervening galaxies.

Even if we accept that most absorptions are due to extrinsic intervening systems (e.g. Sargent et al., 1979) it is still not clear which type of system is chiefly responsible. Absorption by normal galaxies encounters the well-known problem (Burbidge et al., 1977) that the cross-section for observable lines must be very large in order to account for the number of systems seen. Halo sizes typically $\sim 50\, h^{-1}$ kpc, several times the optical Holmberg radius, are required (Sargent et al., 1979; Weymann et al., 1979; Young et al., 1982). The other alternative is that the absorption occurs in extremely numerous, but presently unseen, low surface brightness galaxies (Impey and He, 1986, henceforth IH; Disney and Phillipps, 1987).

Clearly we can only hope to distinguish between these possibilities by a uniform study of a sufficient number of QSOs, and an obvious strategy is to concentrate on a sample of QSOs behind the Virgo cluster (cf. IH). The QSO counts of Véron and Véron (1982) imply that sufficient numbers should be detectable, at a reasonable magnitude limit, for a statistical study to be made, though only a small number have so far been identified (He et al., 1984).

In the present paper we describe computer simulations designed to estimate the numbers and column densities of absorption lines to be expected in QSOs behind Virgo as galaxy halo sizes and the numbers of dwarf galaxies are varied. Such calculations may allow limits to be placed on the number of low surface brightness galaxies in Virgo when a sufficiently large sample of background quasars becomes available. An obvious difficulty is that direct measurements of the hydrogen column densities (as used here) from Lyman lines require observations in the UV, for example with the Space Telescope. To interpret metal line column densities, we would need to assume something about the metallicity of galactic halos and very low surface brightness galaxies further complicating the analysis.

2. The model

The computer simulation comprises two separate parts, the generation of a cluster of galaxies designed to imitate Virgo (in a statistical sense) and the calculation of the absorption systems then expected for a network of randomly placed background QSOs.

IH have previously presented a discussion of the numbers of specific known quasars close to catalogued Virgo cluster galaxies in Huchra's list (cf. Huchra et al., 1983). We have adopted the alternative approach of modelling a non-specific galaxy cluster which has, nonetheless, the same overall properties as Virgo. The numbers of each morphological type of galaxy and the corresponding luminosity functions have been taken from the Virgo Cluster Catalogue studies of Sandage and collaborators (Binggeli et al., 1984; Binggeli et al., 1985, Sandage and Binggeli 1984; Sandage et al., 1985a, b; henceforth collectively VCC). Background members have been excluded and possible members assigned half weight in the luminosity functions. We also allow ourselves a varying number L of additional low surface brightness (Im) dwarf galaxies in the model runs. The maximum L we have taken is 3000, (3000 over the area considered here corresponds to ~ 40 per square degree over the Virgo region as a

Send offprint requests to: J.I. Davies whole). We take the Im luminosity function to have a Schechter (1976) form with $M_* = -16.1$, $\alpha = -1$ (i.e. constant number per magnitude interval at faint limits), cut off at $M_B = -10$ (for ease of comparison we assume a distance modulus of 31.7 as in the VCC).

In generating the description of a particular galaxy of a particular morphological type and magnitude we further assign it a bulge to disc ratio according to the distribution given by Simien and de Vaucouleurs (1986). Central surface brightness distributions (assumed gaussian) are taken from Boroson (1981) for discs and bulges and Allen and Shu (1979) for ellipticals (since the latter do not play an important role we have not included a surface brightness-luminosity correlation for ellipticals as given by e.g. Kormendy, 1977). We take standard exponential and de Vaucouleurs' $r^{1/4}$ law profiles for discs and bulges/ellipticals respectively: corresponding scale sizes can then be calculated from the assigned magnitude and central surface brightness.

The coordinates of the galaxies are generated such that the observed radial projected density variation ($\propto \rho^{-1}$) and the increase in the proportion of E and $S0$ types towards the centre are reproduced (cf. Tully and Shaya, 1984). The simulated area represents the central $5° \times 5°$.

Secondly we generate a set of random background QSO positions. Véron and Véron's (1982) counts give an expected value of 36 QSOs per square degree at $B = 20.4$. This gives $\simeq 900$ such objects in the simulated area. Results from IH in fact indicate that QSOs behind Virgo may be depleted by a factor 2 (cf. Shanks et al., 1983; Phillipps, 1986) giving ~ 450 in our area. All the simulations have been run for a network of 450 background QSOs.

The QSO positions are then checked against the galaxy list to determine the angular separation from the various galaxy centres. We assume that the QSO will not be seen if it lies behind the central core of a galaxy image, defined by the isophotal radius R_{23} at the 23 B magnitudes per square arcsecond ($23B\mu$) level. This has the effect of slightly concentrating the QSOs into inter-galaxy regions (cf. Phillipps, 1986). At the other extreme, if the line-of-sight to the quasar does not pass within NR_H of a cluster member, where R_H is the galaxy's Holmberg radius ($\equiv R_{26.5}$) and $1 \leqslant N \leqslant 5$ depending on the run, then we do not ascribe any absorption lines to the QSO (here and elsewhere, by absorption line we mean an absorption line, or system, at the redshift of Virgo). A maximum galaxy size of $5R_H$ has been used as this may be considered a reasonable limit to the H I or neutral gas halo size in a cluster environment (see also IH). At low densities $\lesssim 10^{19}$ cm^{-2}, the hydrogen is likely to be ionised by the UV background (Rees, private communication) so a halo cut-off at around this level may be unavoidable. Galaxies with large H I radii have been found (e.g. Krumm and Burstein, 1984) but are by no means common. More typical sizes quoted in the literature are 2–3R_H (e.g. Bosma, 1981a, b). Direct observations of metal line absorption systems in quasars behind visible galaxies also imply the existence of absorbers at distances $\sim 3R_H$ from the centres of galaxies (e.g. Bergeron, 1986; Cristiani, 1987).

To calculate the associated column densities due to galaxies between R_{23} and NR_H from the quasar line-of-sight we obviously need to model the H I profile, and we have used the following simplified but reasonably realistic form which agrees satisfactorily with the data over the appropriate ranges.

First of all E and dE galaxies are assumed to be gas poor (Knapp et al., 1977; Bothun et al., 1985) and hence to have negligible absorption effects. For spirals the column density is assumed proportional to the light intensity out to the de Vaucouleurs radius R_{25}, with a conversion factor corresponding to $M_H/L_B = 0.125$ (cf. Sullivan et al., 1981). Outside R_{25} (where by construction $N_{HI} = 1.5\ 10^{20}$ cm^{-2}) we assume a slower exponential decline such that $N_{HI} = 1\ 10^{20}$ cm^{-2} at $1.5R_H$, in order to model the outer halo (cf. Bosma, 1981a). Note that this means that for a cut-off at $\lesssim 5R_H$ we are always dealing – in our basic model – with absorbers with N_{HI} at least a few $\times 10^{19}$ cm^{-2} (because of the smooth exponential distribution we initially assume). On the other hand, most observations of metal line systems far out in galaxy halos correspond to column densities of a few $\times 10^{18}$ cm^{-2} (e.g. Bergeron, 1986; Bechtold et al., 1984), and as noted earlier direct measurements of the H I profiles (Bosma, 1981a, b; Briggs et al., 1980; Sancisi, 1987) show that in most systems the column density drops steeply beyond $\sim 2R_H$. Our initial model was chosen to be consistent with metal line absorption systems of QSOs being produced in smoothly extended galactic halos since Briggs et al. (1980) pointed out that halos with a sharp decline in column density beyond $2R_H$ pose "a dilemma for the intervening galaxy hypothesis because it is difficult to envisage such a large metal abundance at such large radii". The alternative model for extended H I halos would therefore require an extended component at the few $\times 10^{18}$ cm^{-2} level beyond the extrapolation of the inner component used in our simple model. Unfortunately very little is known about the typical H I profile of galaxies at these levels. However we can easily predict the effect of such a change in our halo model, as discussed in Sect 3 below. The low surface brightness Im galaxies, modelled as exponential discs with central surface brightness 23.2 ± 1.0 $B\mu$, have been assumed to be gas rich with $M_H/L_B = 0.5$ (cf. Longmore et al., 1982). [Note that in practice the individual values of 23.2 $B\mu$ and M_H/L_B are not critical, their product (column density $\propto (M_H/L_B)\ 10^{-0.4s}$) being the important factor. This means that we can equally well be modelling even lower surface brightness objects with correspondingly higher M_H/L_B, as observed, cf. Phillipps and Disney, 1983].

Note also that in the above we have taken the Virgo cluster galaxies to be H I deficient by a factor 2 (Hoffman et al., 1985; Haynes et al., 1984) i.e. we have used M_H/L_B values which are only a half of those given in the quoted papers. To recover the values for a non-deficient population we can simply multiply the final column densities by 2, the numbers of absorptions being unaffected. If the deficiency is instead in the form of a loss of gas from the outer parts then the model runs with small halos will already account for this possibility. In all cases we have assumed that there is a rapid decline in column density beyond the radius NR_H (cf. Bosma, 1981a) and have simply cut off the profile at that point.

3. Results and discussion

The results given by the simulations are summarised in Figs 1 and 2. The quantities plotted are the fraction of quasars with at least one absorption system (i.e. detections), f, the mean column density (for the detections only). $\langle N_{HI} \rangle$ in units of 10^{20} cm^{-2} (Fig. 1) and the average number of separate systems along a line-of-sight (again for the detections only), $\langle N_l \rangle$ (Fig. 2). The latter should be easily resolved since the relative peculiar velocities of a pair of galaxies will be typically ~ 1000 km s^{-1}, rather larger than intercloud velocities in a given galaxy halo (< 300 km s^{-1}).

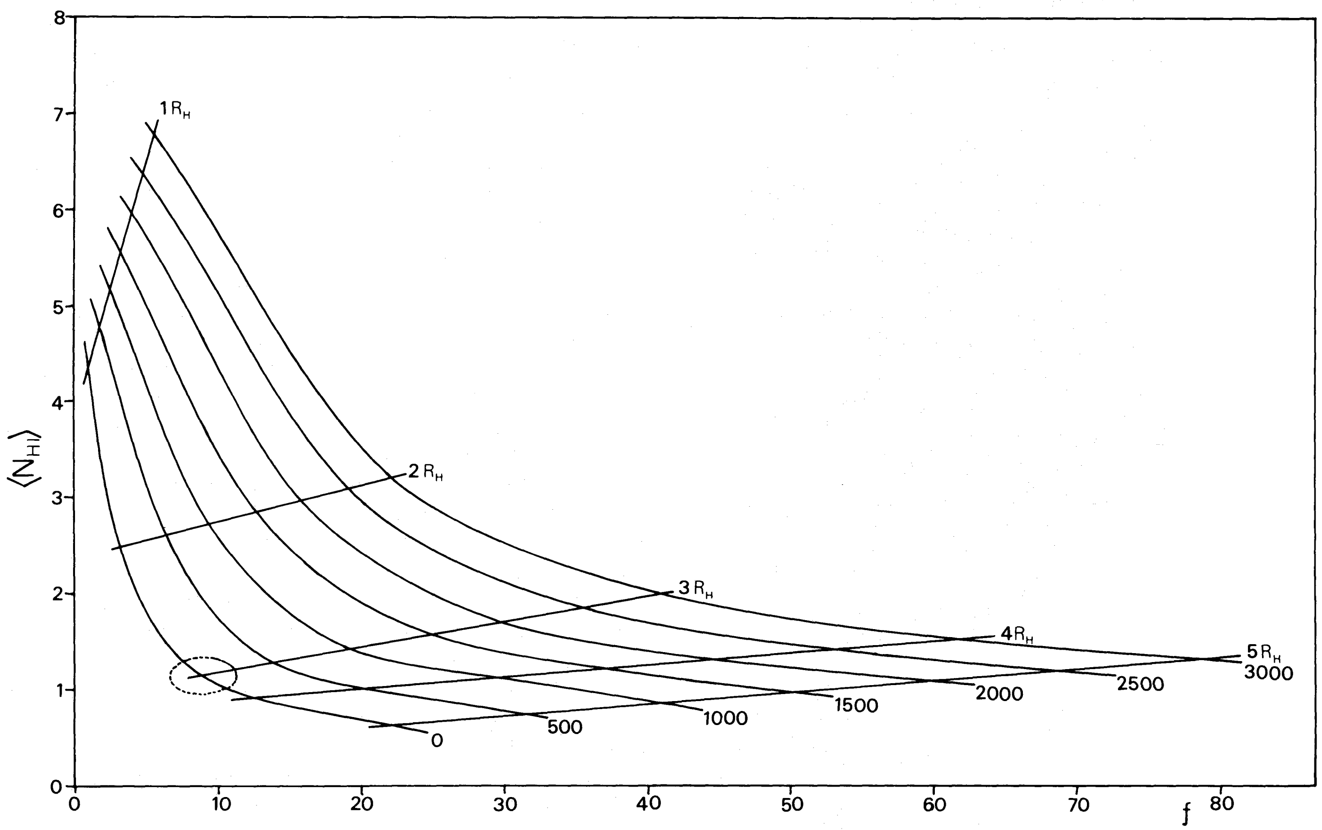

Fig. 1. Percentage with at least one absorption feature (f) against mean column density ($\langle N_{\rm H\,I}\rangle$) in units of 10^{20} cm^{-2}. Numbers refer to the galactic halo size and numbers of extra dwarf galaxies. The dotted line indicates the size of the error ellipse at each point. If lower column density outer halos are used, the points at $>2R_{\rm H}$ are reduced by $\sim 30\%$ (see text)

Note that in our basic model we are only considering relatively high column density absorbers is ($\langle N_{\rm H\,I}\rangle$ $10^{19}\,{\rm cm}^{-2}$); it may of course be difficult in practice to isolate these systems, though possibly the damped $Ly\alpha$ absorbers of Wolfe et al. (1986) could be utilised. Note also that typical column densities of a few $\times 10^{20}\,{\rm cm}^{-2}$, as in Fig. 1, are consistent with a reduction in the number of observed quasars by a factor 2 (IH) since this requires optical absorption $A_B \approx 0^{\rm m}3$ (Phillipps, 1986), corresponding for normal dust:gas ratios to $N_{\rm H\,I} = 3\,10^{20}$.

The individual numbers in the figures indicate runs with halo sizes $NR_{\rm H}$, $N = 1, \ldots, 5$, and for the various numbers of LSBGs (in addition to the standard VCC galaxy population) ranging from 0 to 3000. The hand-drawn curves indicate the overall trends in the plotted quantities. It can be seen that the $\langle N_{\rm H\,I}\rangle$ *versus* f plot gives a much cleaner separation between the models (especially for different halo sizes). On the other hand it is somewhat more model dependent (requiring the detailed H I profiles), so the $\langle N_1\rangle$ *versus* f plot is useful as a check.

As discussed earlier, our initial halo model is just a direct extrapolation of the H I profile at intermediate radii ($\sim R_{\rm H}$). If we adopt a halo with much lower column densities beyond some cut-off radius $\sim 2R_{\rm H}$ then we can easily predict the effect this will have on Fig. 1. (Fig. 2 will of course be unchanged).

Firstly those points interior to $2R_{\rm H}$ will be unaffected but those for larger halos will have lower values of $\langle N_{\rm H\,I}\rangle$ than before while the values of f stay the same. Now the mean column density for detected lines

$$\langle N_{\rm H\,I}\rangle_N = \sum_{1}^{N_{\rm Q} f_N} n_i / N_{\rm Q} f_N$$

where the n_i represents the individual column densities of the detected halos, $N_{\rm Q}$ is the total number of QSOs (450) and f_N is the fraction with absorption lines for halo size $NR_{\rm H}$. In the case where $N_{\rm H\,I}$ is negligible ($\sim$few $\times 10^{18}$) outside a steep cut-off at $2R_{\rm H}$ (where $N_{\rm H\,I} \sim$several $\times 10^{19}$), then

$$\langle N_{\rm H\,I}\rangle_N = \sum_{1}^{N_{\rm Q} f_2} n_i / N_{\rm Q} f_N$$

i.e. $\langle N_{\rm H\,I}\rangle_N = \langle N_{\rm H\,I}\rangle_2 f_2 / f_N$, for $N > 2$.

From Fig. 1 we can see that the factor f_N/f_2 is roughly 2 for $N = 3$, 3.5 for $N = 4$ and 5.5 for $N = 5$. Dividing the plotted values of $\langle N_{\rm H\,I}\rangle_2$ by these amounts we can see that the change relative to the original halos is not very large ($\sim 30\%$). For instance taking the upper curve in the figure (i.e. numerous dwarfs) we see that $\langle N_{\rm H\,I}\rangle_2 \simeq 3\,10^{20}$, leading by the above argument to $\langle N_{\rm H\,I}\rangle_3 \simeq 1.5\,10^{20}$ (the plotted value is $\simeq 2\,10^{20}$), $\langle N_{\rm H\,I}\rangle_4 \simeq 1\,10^{20}$ (previously $\simeq 1.5\,10^{20}$) and $\langle N_{\rm H\,I}\rangle_5 \simeq 0.6\,10^{20}$ (previously $\simeq 1\,10^{20}$). Obviously this is the extreme case, and if we took into account the real halo column densities in the outer halos, the values would be even closer to those plotted. The overall shape of Fig. 1 would in any case be basically unchanged.

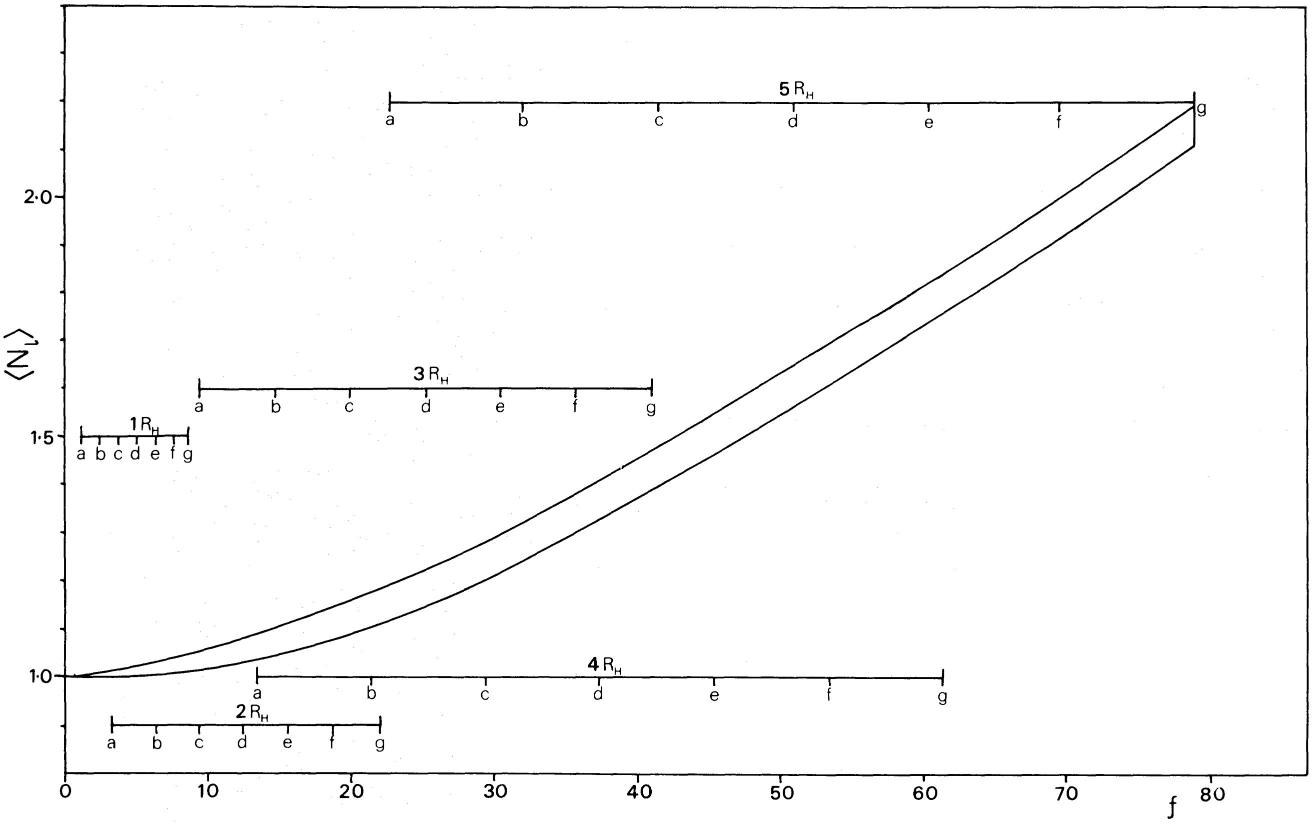

Fig. 2. Percentage with at least one absorption feature against number of haloes on a line-of-sight. Horizontal lines indicate range of each halo size for various populations of: a = 0, b = 500, c = 1000, d = 1500, e = 2000, f = 2500, g = 3000 extra dwarf galaxies

We can immediately note some general consequences of our model:

1) With no LSBGs, as is well known, in order to get a significant number of absorption line systems (at levels $N_{\rm HI} > 10^{19}$ cm^{-2}) we require very large halos. With $4R_{\rm H}$ halos we predict that $\sim 13\%$ of quasars should have absorption systems in excellent agreement with the 10 out of $\simeq 70$ predicted by IH for their specific quasars and quasar candidates.

2) If about $5R_{\rm H}$ is the maximum allowable halo size, due to galaxy-galaxy interactions, then we can obtain no more than $\sim 25\%$ detections, unless we admit large numbers of LSBGs. Our model with 3000 LSBGs (and $5R_{\rm H}$ halos) allows up to $\simeq 80\%$ detections.

Some further more specific (i.e. more model dependent) implications are that

3) The inclusion of numerous LSBGs increases the fraction of detections and the mean column densities; the detection of high column densities at any particular f favours the LSBG hypothesis (where we have numerous small high $N_{\rm HI}$ areas) over the very large halos (which obviously add in more low column density lines-of-sight).

4) In particular, observing few, but high $\langle N_{\rm HI} \rangle$ systems would imply small halos and numerous LSBGs.

5) A large number of overlapping galaxies (i.e. multiple systems) cannot be obtained from the VCC galaxy population alone. If large numbers of multiple systems are observed ($\langle N_{\rm I} \rangle \simeq 2$) with appropriate splitting > 300 km s^{-1} then this indicates numerous LSBG with large haloes.

Acknowledgements. We would like to thank Dr. J. Bergeron for her useful comments and for refereeing this paper. JD acknowledges the receipt of an SERC postgraduate studentship and SP an SERC Advanced Fellowship.

References

Allen, R., Shu, F.: 1979, *Astrophys. J.* **227**, 67
Arp, H.: 1965, *Astrophys. J.* **142**, 402
Bechtold, J., Green, R., Weyman, R., Schmidt, M., Estabrook, F., Sherman, R., Wahlquist, H., Heckman, T.: 1984, *Astrophys. J.* **281**, 76
Bergeron, J.: 1986, *Astron. Astrophys.* **155**, L8
Binggeli, B., Sandage, A., Tarenghi, M.: 1984, *Astron. J.* **89**, 64
Binggeli, B., Sandage, A., Tammann, G.: 1985, *Astron. J.* **90**, 1681
Boroson, T.: 1981, *Astrophys. J. Suppl.* **46**, 177
Bosma, A.: 1981a, *Astron. J.* **86**, 1791
Bosma, A.: 1981b, *Astron. J.* **86**, 1825
Bothun, G.: 1986, in *Nearly Normal Galaxies*, ed. S.S. Faber, Springer, New York
Bothun, G., Mould, J., Wirth, A., Caldwell, N.: 1985, *Astron. J.* **90**, 697
Briggs, F., Wolfe, A., Krumm, N., Salpeter, E.: 1980, *Astrophys. J.* **238**, 510
Burbidge, S., O'Dell, L., Roberts, H., Smith, H.: 1977, *Astrophys. J.* **218**, 33
Cristiani: 1987, *Astron. Astrophys.* **175**, L1

Disney, M., Phillipps, S.: 1987, Proc Vatican Conference (in press)

Haynes, M.P., Giovanelli, R., Chincarini, G.: 1984, *Ann. Rev. Astron. Astrophys.* **22**, 445

He, X.-T., Cannon, R., Peacock, J., Smith, M., Oke, J.: 1984, *Monthly Notices Roy. Astron. Soc.* **211**, 443

Hoffman, G., Helou, G., Salpeter, E., Sandage, A.: 1985, *Astrophys. J. Letters* **289**, L15

Huchra, J., Davis, M., Latham, D., Tonry, J.: 1983, *Astrophys. J. Suppl.* **53**, 39

Impey, C., He, X.-T.: 1986, *Monthly Notices Roy. Astron. Soc.* **221**, 897

Krumm, N., Burstein, D.: 1984, *Astron. J.* **89**, 1319

Kormendy, J.: 1977, *Astrophys. J.* **217**, 406

Knapp, G., Gallagher, J., Faber, S., Balick, B.: 1977, *Astron. J.* **82**, 106

Longmore, A., Hawarden, T., Goss, W., Mebold, U., Webster, B.: 1982, *Monthly Notices Roy. Astron. Soc.* **200**, 325

Phillipps, S.: 1986, *Astrophys. Letters* **25**, 19

Phillipps, S., Disney, M.: 1983, *Monthly Notices Roy. Astron. Soc.* **205**, 563

Sancisi, R.: 1987, in STScI Workshop on *QSO Absorption Lines*

Sandage, A., Binggeli, B.: 1984, *Astron. J.* **89**, 919

Sandage, A., Binggeli, B., Tammann, G.: 1985, *Astron. J.* **90**, 395

Sandage, A., Binggeli, B., Tammann, G.: 1985, *Astron. J.* **90**, 1759

Sargent, W., Young, P., Boksenberg, A., Carswell, R., Whelan, J.: 1979, *Astrophys. J.* **230**, 49

Schechter, P.: 1976, *Astrophys. J.* **203**, 297

Shanks, T., Fong, R., Green, M., Clowes, R., Savage, A.: 1983, *Monthly Notices Roy. Astron. Soc.* **203**, 181

Simien, F., de Vaucouleurs, G.: 1986, *Astrophys. J.* **302**, 564

Sullivan, W., Bothun, D., Bates, B.: 1981, *Astron. J.* **86**, 919

Tully, R., Shaya, E.: 1984, *Astrophys. J.* **281**, 31

Veron, P., Veron, M.: 1982, *Astron. Astrophys.* **105**, 405

Weyman, R., Williams, R., Peterson, B., Turnshek, D.: 1979, *Astrophys. J.* **234**, 33

Wolfe, A., Turnshek, D., Smith, H., Cohen, R.: 1986, *Astrophys. J. Suppl. Ser.* **61**, 249

Young, P., Sargent, W.L., Boksenberg, A.: 1982, *Astrophys. J.* **252**, 10