Halo Kinematics

Terry Bridges

Institute of Astronomy, Madingley Road, Cambridge, UK, CB3 0HA

Abstract.

I summarize recent observations of the kinematics of hot tracers in elliptical galaxy halos (globular clusters, planetary nebulae, and integrated stellar light), and what these tell us about the dynamics, dark matter content, and formation of ellipticals. A generic result is the ubiquity of dark matter halos in ellipticals. Studies of globular clusters and planetary nebulae are now finding outer-halo rotation in many ellipticals, with $V/\sigma \simeq 1$ beyond a few $R_e$. In some giant ellipticals (M49, M87), there are possible kinematic differences between metal-poor and metal-rich globular clusters. These results are consistent with a merger origin for ellipticals. High-quality data and new modelling techniques now make it possible to determine simultaneously the orbital anisotropy and gravitational potential in ellipticals from integrated-light measurements; such studies now provide the best evidence for dark matter halos in ellipticals. The new generation of 8–10m telescopes, with multi-object and integral-field spectrographs, will dramatically increase sample sizes of discrete tracers and provide two-dimensional spectroscopy of elliptical halos. New methods of analysis will allow robust determinations of stellar kinematics and dark matter distributions in a much larger number of ellipticals. Comparison with numerical simulations, which are becoming ever more detailed and physically realistic, will become increasingly important.

1. Introduction and Motivation

Why Study the Halo Kinematics of Elliptical Galaxies?

There are several important subjects that we can address via the spectroscopy of hot tracers in elliptical galaxy halos:

- The amount and distribution of dark matter in elliptical halos.
  Recent N-body simulations of the formation of galaxy halos in hierarchical clustering scenarios (e.g. Navarro et al. 1997) predict that elliptical galaxies have dark matter halos with a mildly cusped universal density profile. It is obviously important to check this observationally.

- The kinematics (i.e. velocity distributions) of elliptical halo populations.
  We would like to determine the rotation, velocity dispersion, and velocity anisotropy for different halo populations, as far into the halo as possible.
• **Testing of formation models for elliptical galaxies.**

In principle, the different formation models make different predictions for the kinematics of halo populations. In this review I will concentrate on two main classes of formation models: monolithic/multiphase collapse, and mergers (hierarchical or otherwise).

**Why is it Difficult?**

Spiral galaxies conveniently have excellent kinematical tracers, in the form of rotating disks of neutral and ionized gas, extending over a wide range of radii. In contrast, we know much less about the dark matter content and dynamics of elliptical galaxies. Masses have been measured from X-ray observations or HI ring velocities for some ellipticals, and for others various methods described in this review have allowed us to rule out constant M/L ratios. However, the detailed radial mass distributions of elliptical galaxies are almost totally unknown.

The problem is a fundamental degeneracy between *stellar orbits* and the underlying *gravitational potential*. Stellar test particles can occupy a wide range of different orbits in a given potential, and the degeneracy cannot be removed from rotation and velocity dispersion data alone (e.g. a rising velocity dispersion could be due to either tangential anisotropy or a dark matter halo). Only recently have high-quality data and new modelling techniques allowed the simultaneous determination of the anisotropy and mass distribution from measuring the *shape* of the line-of-sight velocity distribution (LOSVD) (Section 4).

**Outline of This Review**

In this paper I will concentrate on recent observational studies of the kinematics and dark matter content of elliptical galaxy halos, with some discussion of the implications for the formation of elliptical galaxies. This is not intended to be a complete review of the field, and I will point the reader to earlier reviews. I will not discuss the *shapes* of dark matter halos (see review by P. Sackett in this volume), nor the abundance information that can also be obtained from halo spectroscopy (see for instance the review by R. Bender in this volume). In Section 2, I will discuss planetary nebulae; in Section 3, globular clusters; and in Section 4, integrated-light measurements. In Section 5 I present my main conclusions and predictions/hopes for the future.

### 2. Planetary Nebulae

Here I will concentrate on results obtained in the last five years. For an excellent review of earlier work, see Arnaboldi & Freeman (1997).

#### 2.1. The Usefulness of Planetary Nebulae

Planetary nebulae (PNe) are excellent dynamical probes because:

- They are bright; \(\sim 15\%\) of their energy goes into a single emission line of [OIII] at 5007 Å.

- They are easy to detect: one ‘simply’ compares an image taken with a narrow-band filter centered on [OIII] with one taken off-band. Once PNe
have been identified, multi-object spectroscopy with high dispersion allows velocities to be obtained with a precision better than 50 km/sec. Very clean samples are obtained in this way, with very little contamination.

- They are numerous, even in early-type galaxies, and hundreds of PNe can be measured with 4m class telescopes in galaxies out to the distance of Virgo and Fornax. With 8–10m class telescopes, as many as 500 PNe can be measured in the brightest galaxies in these clusters.

2.2. Observational Summary

Table 1 gives an overview of recent dynamical studies of ellipticals using PNe. Column 3 gives the number of PNe with measured velocities, Column 4 the galactocentric radius of the most distant measured PNe, Column 5 the M/L ratio in the B band in solar units, and Column 6 the PNe rotation amplitude.

| Galaxy     | Authors               | N_{PNe} | Radius (kpc) | M/L_B   | Rotation (kms^{-1}) |
|------------|-----------------------|---------|--------------|---------|---------------------|
| NGC 3379   | Ciardullo et al. 1993 | 29      | 10           | 7       |                     |
| NGC 1399   | Arnaboldi et al. 1994 | 37      | 16           | $\sim$80 | 290                 |
| NGC 3384   | Tremblay et al. 1995  | 68      | 7            | $>9$    | 125                 |
| NGC 4406   | Arnaboldi et al. 1996 | 16      | 19           | 13      | 250                 |
| NGC 1316   | Arnaboldi et al. 1998 | 43      | 16           | 8       | 100                 |
| NGC 5128   | Peng et al. 1998      | 657     | 40           | 15      | 100                 |

Some general comments about Table 1 may be made:

- The power of PNe for studying elliptical halos is demonstrated by the fact that the measurements extend to at least 2 R_e in every galaxy.
- The M/L ratio is invariably increasing outwards, from central values $\sim$ 5 to values of typically 10–20 at larger radius: dark matter halos seem to be a common feature of elliptical galaxies.
- There is almost always detectable rotation in the PNe; the halos of elliptical galaxies contain a large amount of angular momentum (see below).

Further Discussion

**NGC 1399 and Fornax Intracluster PNe**

NGC 1399 is a giant elliptical galaxy situated at the center of the nearby Fornax cluster. Arnaboldi et al. (1994) measured a large rotation ($\sim$ 300 km/sec) for the PNe in NGC 1399, showing that the total specific angular momentum J/M of ellipticals can in fact be comparable with that of giant spirals, in agreement with cosmological simulations of elliptical formation. Arnaboldi et al. also suggested that the large M/L ratio of NGC 1399 was due to PNe responding more to the potential of the Fornax cluster than to the galaxy itself; Figure 1 of Kissler-Patig (1998; this volume) shows that there is indeed a
transition from the galaxy to cluster, as traced by stars, PNe, globular clusters, cluster galaxies, and X-ray gas, at progressively larger radius. Such intracluster PNe complicate efforts to study cluster galaxies, but are obviously extremely important in terms of studying the clusters themselves. This is an active field, with several ongoing searches in the Fornax and Virgo clusters.

NGC 1316

The work of Arnaboldi et al. (1998, also this volume) on NGC 1316 is noteworthy because it is one of the first attempts to combine PNe and integrated-light data. The smoothed velocity field of the combined PNe and absorption-line data (Figure 1) allows the rotation curve in NGC 1316 to be traced from the galaxy center out to \( \sim 16 \) kpc, and reveals significant outer-halo rotation in this galaxy. With larger samples of discrete tracers and with the further addition of X-ray and gravitational lensing data at larger radius, such techniques will be a powerful way to study the dynamics and mass distributions of ellipticals.

NGC 5128

Combined studies by Hui et al. (1995) and Peng et al. (1998, this volume) of the nearby peculiar elliptical NGC 5128 (Centaurus A), have amassed the largest number of PNe velocities in any elliptical and the best radial coverage. Hui et al. were able to show that the velocity field of the PNe is likely triaxial, and both studies show significant rotation out to large radius. Figure 2 shows the enclosed mass as a function of radius using the Projected Mass Estimator (PME; Heisler, Tremaine & Bahcall 1985), taken from Peng et al.

3. Globular Clusters

3.1. Introduction

Globular clusters share many of the advantages of PNe: they are bright \((M_V \simeq -7)\) and especially numerous in early-type galaxies. However, since they are absorption-line objects, long integrations are required (the absorption lines,
however, can also be used to obtain precious abundance information). I will concentrate on work done since the review by Brodie (1993).

3.2. Observational Summary

Table 2 gives an overview of recent dynamical studies of (mostly!) elliptical galaxies using globular clusters; it has the same format as Table 1.

| Galaxy    | Authors                  | N_{cl} | Radius (kpc) | M/L_B | Rot (kms^{-1}) |
|-----------|--------------------------|--------|--------------|-------|----------------|
| M31       | Perrett et al. 1998      | 220    | 20           | –     | ~ 125          |
| M81       | Perelmutter et al. 1995  | 25     | 19           | 19    | –              |
| M104      | Bridges et al. 1997      | 34     | 14           | 22    | 75             |
| M49       | Zepf et al. 1998         | 144    | 50           | ~ 70  | 100            |
| NGC 3115  | Kavelaars et al. 1998    | 22     | 14           | 20    | 190            |
| NGC 1399  | Grillmair et al. 1994    | 47     | 50           | 70–80 | –              |
| NGC 1399  | Kissler-Patig et al. 1998a | 18     | 28           | ~ 35–75   | –              |
| NGC 1399  | Minniti et al. 1998      | 18     | 28           | 50–130 | –             |
| NGC 1399  | Kissler-Patig et al. 1998b | 74     | 50           | 150–200 | 150??          |
| M87       | Cohen & Ryzhov 1997      | 205    | 40           | 30    | 100            |
| M87       | Kissler-Patig & Gebhardt 1998 | 205    | 40           | –     | 300            |

The general comments made about PNe in Section 2.2 also apply to globular clusters: the data extend out to 5–10 R_e, and support the existence of dark matter halos in virtually every elliptical studied. There is also evidence for outer-halo rotation in some ellipticals, similar to that found in PNe.

Further Discussion

*M87/Virgo and NGC 1399/Fornax*
These two centrally-located gE/cD galaxies have been the object of several studies, as shown in Table 2. I will only touch on a couple of interesting recent results, since M87 and NGC 1399 are both reviewed by Kissler-Patig (1998; this volume). In NGC 1399, Kissler-Patig et al. (1998b) have combined the available globular cluster velocities, and found evidence for rotation in the outer-most clusters (beyond 5 arcmin radius), an interesting result in light of the large rotation found in the NGC 1399 PNe by Arnaboldi et al. (1994) (but in the opposite sense to the globular clusters! See Kissler-Patig for more details).

Cohen & Rhyzov (1997) obtained velocities and spectroscopic metallicities for 205 globular clusters in M87. From Figure 3, taken from Cohen & Rhyzov, we see that the globular cluster velocity dispersion increases outwards. This is similar to what is seen in NGC 1399/Fornax, and in both cases it is likely that we are seeing the transition from the galaxy to the cluster. Kissler-Patig & Gebhardt (1998) have re-analyzed the Cohen & Rhyzov data, and found that the metal-poor clusters have a higher rotation (∼ 300 km/sec) than the metal-rich clusters (∼ 100 km/sec); this is only a 1-σ result, however.

M49/NGC 4472

M49 (=NGC 4472) represents a different environment than M87, being the central gE in a Virgo southern subcluster. Thus, we expect less contamination from any intrachuster globular clusters, and a better determination of the dynamics and dark matter of M49 itself. The Washington photometry of Geisler et al. (1996) shows that the globular cluster colour distribution is clearly bimodal, with corresponding metallicity peaks at [Fe/H] = −1.3 and −0.1.

We (Sharples et al. 1998) obtained velocities for ∼ 50 globular clusters in M49 at the WHT. We found tentative evidence for kinematic differences
between the red (metal-rich) and blue (metal-poor) globular clusters, with the blue clusters having both a higher velocity dispersion and rotation. We now have 144 cluster velocities, with the addition of recent CFHT data (Zepf et al. 1998). Figure 4 shows that the velocity dispersion difference between the red and blue clusters still holds with the larger sample, as does the difference in rotation (though the latter is still only marginally significant). The larger rotation in the more extended blue cluster system is consistent with a merger origin for M49, since mergers are efficient at transporting angular momentum outwards (e.g. Hernquist & Bolte 1993). As noted above, a similar result has been found more recently by Kissler-Patig & Gebhardt (1998) for the M87 globular clusters.

![Velocity histograms for M49 globular clusters, taken from Zepf et al. (1998). Left: Metal-poor clusters; Right: Metal-rich clusters. The difference in velocity dispersion between the metal-poor and metal-rich clusters is significant at better than 99%.](image)

We have used the globular cluster velocities and Projected Mass Estimator (assuming isotropic orbits and an extended mass distribution), to find a mass of $4.5 \times 10^{12} M_\odot$ and $M/L_B$ ratio of $\sim 70$ at 50 kpc ($6 R_e$) for M49; these values are comparable to those found in M87 and NGC 1399 from similar studies. Figure 5 shows that the mass as determined from the globular clusters agrees quite well with that found from ROSAT X-ray data by Irwin & Sarazin (1996).

4. Integrated-Light Studies

4.1. Introduction

Studies of the stellar component (integrated-light) in elliptical galaxies complement dynamical studies at larger radius with globular clusters, PNe, and X-ray data. With integrated-light data, there are not the same sample size problems as with discrete tracers, but the radially decreasing surface brightness of elliptical halos restricts such measurements to within $\sim 3 R_e$ of the galaxy center (at least with 4m-class telescopes).
This field is undergoing a renaissance with recent advances in observations and analysis techniques. Observationally, we now have better CCDs, sky-subtraction techniques, and the careful use of stars of different spectral types for template matching. There is an awareness of the need for long-slit spectroscopy with several position angles, and now integral-field spectrographs can provide full two-dimensional coverage, although with small fields.

Theoretically, a major step forward has been the development of analysis techniques utilizing the *entire* Line-of-Sight Velocity Distribution (LOSVD) (e.g. Rix & White 1992; van der Marel & Franx 1993), not just the lowest moments $V$ and $\sigma$. With the incorporation of these higher-order moments, the degeneracy between stellar orbits and gravitational potential can be removed and in principle both can be determined simultaneously. There are many possible schemes; see papers by N. Cretton and S. de Rijcke in this volume for further details. As I will show below, recent studies using these techniques on high-quality data give very strong evidence for dark matter halos in ellipticals.

### 4.2. A Selected Review of Recent Work

This review is far from exhaustive, and is meant only to indicate the flavour and potential of recent work.

*Saglia et al. 1993*

This work represents the beginning of the ‘modern era’ in studies of integrated light in ellipticals. Saglia et al. obtained major-axis spectra out to 2 $R_e$ for NGC 4472, NGC 7144, and IC 4296, and found suggestive evidence that the M/L ratio increases outwards in all three.

*Carollo et al. 1995*
Carollo et al. obtained major-axis spectra out to 2–2.5 $R_e$ for NGCs 2434, 2663, 3706, and 5018. They carried out Gauss-Hermite modelling of the LOSVDs, and found that strong tangential anisotropy can be ruled out at large radii: i.e., there are very likely dark matter halos in all of these galaxies.

Rix et al. 1997

Rix et al. measured the LOSVD out to 2.5 $R_e$ for the E0 galaxy NGC 2434. They used a variation of Schwarzschild’s orbit-building method (see paper by N. Cretton in this volume) to rule out constant M/L models, regardless of the orbital anisotropy. The anisotropy itself is not well-constrained, but the power of the method for studying dark matter halos is apparent.

Gerhard et al. 1998

Gerhard et al. measured the LOSVDs in the E0 galaxy NGC 6703 along the major axis and parallel to the minor axis. They used a new non-parametric technique to determine the Distribution Function directly from the kinematic data, avoiding problems associated with a Gauss-Hermite parameterization. They showed that both the M/L ratio and the anisotropy increase outwards: as for NGC 2434, no model without dark matter will fit the data. Figure 6 shows fits to their $\sigma$ and Gauss-Hermite $h_4$ radial profiles for various luminous plus dark matter potentials, and the inferred anisotropy profile $\beta(r)$.

![Figure 6](image)

Figure 6. Dynamical models for NGC 6703 for various luminous plus dark matter potentials, taken from Gerhard et al. (1998). The top and middle panels show fits to $\sigma$ and Gauss-Hermite $h_4$ respectively, while the bottom panel shows the inferred anisotropy $\beta(r)$. See Gerhard et al. 1998 for more details about the various models.

Statler et al. 1996,1998

The strength of the work by Statler et al. is the good radial coverage (2–3 $R_e$) coupled with spectra taken at four position angles. This allows them to
reconstruct the stellar velocity field, revealing that the galaxy is nearly axisym-
metric. They cannot find a constant M/L model (2 or 3 integral) that will fit
the kinematic data, thus providing firm evidence for a dark matter halo.

Carter, Bridges, & Hau 1998

We have obtained deep major-axis spectra out to $\sim 1 R_e$ (20 kpc) for three
cD galaxies (NGCs 6166, 6173, and 6086). Gauss-Hermite modelling of the
LOSVDs shows that $h_4$ is constant and positive in all three galaxies, suggesting
constant radial anisotropy (though detailed modelling has yet to be done). Thus,
the rising velocity dispersion profile in NGC 6166 (Figure 7) is almost certainly
due to a dark matter halo, and not tangential anisotropy at large radius.

Figure 7. Stellar Kinematics in NGC 6166, from Carter, Bridges, &
Hau (1998). Upper Panel: Stellar velocity dispersion vs. radius. Lower
Panel: Gauss-Hermite parameter $h_4$ vs. radius.

5. Conclusions and the Future

5.1. Summary

- There is firm evidence for dark matter halos in elliptical galaxies, with the
  M/L ratio increasing from 5–10 at small radius to $> 20$ beyond 20 kpc; in
  some galaxies, M/L ratios of 50–100 have been found at larger radius.

- The evidence for dark matter halos is most secure from integrated-light
  studies, where higher order moments of the LOSVD can be used to con-
  strain both the orbital anisotropy and dark matter; in NGC 2434 and NGC
  6703 constant M/L models have been definitively ruled out. Such studies
  most often find stellar radial anisotropy, consistent with recent numerical
  simulations of galaxy formation in CDM universes (e.g. Dubinksi 1998).
• Studies using PNe and globular clusters are still plagued by small samples, and assumptions about the anisotropy have to be made; sample sizes will have to increase by at least an order of magnitude before truly robust conclusions can be drawn.

• There is good evidence for outer-halo rotation in many ellipticals, with $V/\sigma \simeq 1$ beyond a few $R_e$. This is consistent with a merger origin for elliptical galaxies, since hierarchical merging scenarios and N-body simulations of galaxy mergers both predict that ellipticals have significant angular momentum at large radius. Further support for a merger model comes from the finding that the (more spatially-extended) metal-poor globular clusters in M49 and M87 have a larger rotation than the metal-rich clusters.

5.2. The Future

On the observational side, multi-slit spectrographs are allowing us to obtain useful numbers of PNe and globular cluster velocities. There are many ongoing imaging and spectroscopic surveys of globular clusters and PNe, and increasing numbers of integrated-light studies, in early-type galaxies (see several of the papers in this volume). Integral-field spectroscopy of elliptical halos will become increasingly important, especially over large fields. The new generation of 8–10m telescopes with multi-object spectrographs will dramatically increase sample sizes, and allow us to study more distant ellipticals. It will be especially important to carry out more work on field ellipticals, which have been rather neglected to date. With high S/N spectra, we can also hope to obtain globular cluster abundances and ages, which will tell us more about the formation epoch and chemical enrichment of ellipticals. Large telescopes will also allow us to study the integrated-light out to larger radius, and we will be better able to compare the stellar kinematics with globular clusters and PNe.

On the theoretical side, there has been considerable recent work on developing methods to extract the most information from available high-quality integrated-light data, with an emphasis on robust, non-parametric methods. Larger samples of discrete velocities will require new methods of analysis, for instance the non-parametric techniques of Merritt and collaborators (e.g. Merritt & Saha 1993); with 500–1000 (!) velocities per galaxy, both the anisotropy and dark matter can be determined simultaneously. In order to obtain a coherent dynamical picture of elliptical galaxies, we need to develop methods that combine all available kinematic data, and there have been some recent steps in this direction (e.g. Arnaboldi et al. 1998).

Acknowledgments. It is a pleasure to thank Magda Arnaboldi, Nicolas Cretton, Herwig Dejonghe, John Feldmeier, Ken Freeman, J.J. Kavelaars, Ortwin Gerhard, Markus Kissler-Patig, Eric Peng, Hans-Walter Rix, and Tom Statler, for discussions, preprints, and figures. I’d also like to thank my collaborators, Keith Ashman, Mike Beasley, Dave Carter, Doug Geisler, Dave Hanes, Kathy Perrett, and Steve Zepf, for allowing me to discuss our joint work, and for their support and encouragement. Many thanks to the organizers for inviting me to this wonderful conference, and congratulations to the local committee for an excellent job; Monica Valluri, Dave Merritt, and Stacy McGaugh deserve special thanks. I’d like to offer humble apologies to Alex Turnbull and Jim Collett for facing the wrath of the police on my account.
References

Arnaboldi, M., Freeman, K.C. et al. 1994, ESO Messenger, 76, 40
Arnaboldi, M., Freeman, K.C., Mendez, R.H. et al. 1996, ApJ, 472, 145
Arnaboldi, M., & Freeman, K.C. 1997, in The Second Stromlo Symposium: The Nature of Elliptical Galaxies, ASP #116, pg. 54.
Arnaboldi, M., Freeman, K.C., Gerhard, O. et al. 1998, astro-ph 9806253
Bridges, T.J., Ashman, K.M., Zepf, S.E. et al. 1997, MNRAS, 284, 376
Brodie, J.P. 1993, in The Globular Cluster-Galaxy Connection, ASP #48, pg. 483
Carollo, C.M., de Zeeuw, P.T., van der Marel, R.P. et al. 1995, ApJ, 441, L25
Carter, D., Bridges, T.J., & Hau, G.K.T. 1998, submitted to MNRAS
Ciardullo, R., Jacoby, G.H., & Dejonghe, H.B. 1993, ApJ, 414, 454
Cohen, J.G., & Ryzhov, A. 1997, ApJ, 486, 230
Dubinski, J. 1998, ApJ, 502, 141
Geisler, D., Lee, M.G., & Kim, E. 1996, AJ, 111, 1529
Gerhard, O.E., Jeske, G., Saglia, R.P. et al. 1998, MNRAS, 295, 197
Grillmair, C.J., Freeman, K.C., Bicknell, G.V. et al. 1994, ApJ, 422, 9
Heisler, J., Tremaine, S., & Bahcall, J.N. 1985, ApJ, 298, 8
Hernquist, L., & Bolte, M. 1993, in The Globular Cluster-Galaxy Connection, ASP #48, pg. 788
Hui, X., Ford, H.C., Freeman, K.C., & Dopita, M.A. 1995, ApJ, 449, 592
Irwin, J.A., & Sarazin, C.L. 1996, ApJ, 471, 683
Kavelaars, J.J., Hanes, D.A., Sharples, R.M. et al. 1998, in preparation
Kissler-Patig & Gebhardt, K. 1998, astro-ph 9807231
Kissler-Patig, M., Brodie, J.P., Schroder, L.L. et al. 1998a, AJ, 115, 105
Kissler-Patig, M. et al. 1998b, preprint
Merritt, D., & Saha, P. 1993, 409, 75
Minniti, D., Kissler-Patig, M., Goudfrooij, P., & Meylan, G. 1998, AJ, 115, 121
Navarro, J.F., Frenk, C.S., & White, S.D.M. 1997, ApJ, 490, 493
Perlmutter, J.-M., Brodie, J.P., & Huchra, J.P. 1995, AJ, 110, 620
Perrett, K., Bridges, T.J. et al. 1998, in preparation (also this volume)
Rix, H.-W., & White, S.D.M. 1992, MNRAS, 254, 389
Rix, H.-W., de Zeeuw, P.T., Cretton, N. et al. 1997, ApJ, 488, 702
Saglia, R.P., Bertin, G., Bertola, F. et al. 1993, ApJ, 403, 567
Sharples, R.M., Zepf, S.E., Bridges, T.J. et al. 1998, AJ, 115, 2337
Statler, T., Smecker-Hane, T., & Cecil, G.N. 1996, AJ, 111, 1512
Statler, T., Dejonghe, H., & Smecker-Hane, T. 1998, astro-ph 9810046
Tremblay, B., Merritt, D., & Williams, T.B. 1995, ApJ, 443, L5
van der Marel, R.P., & Franx, M. 1993, ApJ, 407, 525
Zepf, S.E., Sharples, R.M., Bridges, T.J. et al. 1998, in preparation