MASS-TO-LIGHT RATIOS OF BINARY GALAXIES

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Le rapport entre le rapport masse-luminosité pour les galaxies de type jeune et celui pour les galaxies de type tardif est égal à 2.0±0.5. La distribution des séparations spatiales r entre paires de galaxies est approximativement une loi en $r^{-1}/2$. Il existe toute une variété de modèles dynamiques pour les systèmes de galaxies binaires. Cependant tous impliquent des rapports masse-luminosité pour les galaxies spirales largement supérieurs aux valeurs conventionnelles (courbe de rotation). L'interprétation la plus plausible des données sur les galaxies binaires implique que les galaxies spirales possèdent des halos contenant ∿10 fois la masse du disque et ont des rapports masse totale - luminosité ∿65 $M_\odot/L_\odot$ (H_o = 50 km s^{-1} Mpc^{-1}).

Rather than repeating the details of a lengthy study of binary galaxy mass-to-light ratios (Turner 1976a, 1976b, 1976c), this contribution will summarize its salient features and results and make a few comments on their significance.

The occurrence of apparently bound pairs of galaxies permits a statistical estimation of galaxian masses and mass-to-light ratios. Such estimates are superior in some ways to those obtained from rotation curve and velocity dispersion studies of individual galaxies and virial theorem analyses of groups and clusters. Unlike the former, binary galaxy mass determinations can measure material well outside the optical object (e.g., a dark halo). And, unlike groups and clusters, binary systems are simple enough to permit the use of an explicit model of the individual galaxy orbits. Because the method is fundamentally a statistical one, it is critically important that the binary systems used in the analysis represent a well-defined statistical sample and that the analysis take into account any biases in the selection of the sample.

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The problem of defining criteria for the selection of binary systems is a central one. For the present study, a number of sets of criteria were considered. The most satisfactory set was adopted and is given by the requirements that

$$\theta_{12} \leq \theta_c \tag{1}$$

and

$$\theta_{12,3} \geq x\ \theta_{12} \tag{2}$$

where θ_{12} is the angular distance from a galaxy 1 to its nearest neighbor 2 and $\theta_{12,3}$ is the angular distance from the middle of the 1-2 system to the next nearest galaxy 3. θ_c is a cut-off radius chosen such that two galaxies are unlikely to satisfy equation (1) by chance projection. The value of x is chosen such that there is only a small chance that the second nearest neighbor to a point is $\geq$ x times farther away than the nearest, if the nearby points are distributed randomly (a probability which is independent of the local density). Essentially, criterion (1) selects pairs which are probably physically associated in some way, while criterion (2) rejects those which are associated through common membership in a group or cluster. These criteria have been applied to galaxies listed in the Catalog of Galaxies and Clusters of Galaxies which satisfy

$$\begin{gathered} \delta > 0° \\ |b^{II}| \geq 40° \\ m_{pg} \leq 15.0 \end{gathered} \tag{3}$$

with $\theta_c = 8'$ and $x = 5$. All position and magnitude data were taken from the CGCG, which contains ~4400 galaxies satisfying (5) (giving a mean density $\overline{\rho} = 1960$). This search yielded a sample of 156 candidate pairs. These systems constitute the sample with which the remainder of this paper will be concerned.

The sample of binary galaxies described above may be analyzed to obtain statistical masses and mass-to-light ratios only if accurate radial velocities are available for a representative and sufficiently large subset of the systems. Velocities available in the literature are unsuitable because they are insufficient in number, embody unknown selection effects, and are probably not accurate enough. Therefore, an observational program designed to obtain a suitable set of radial velocities was undertaken.

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During the spring and fall of 1974 and the spring of 1975, spectrograms of 116 galaxies were obtained with a two-stage image-tube spectrograph at the Ritchy-Chretien focus of the 60-inch (1.5 m) telescope at Mount Palomar. Also during the spring of 1975, spectrograms of 20 more galaxies were obtained with a two-stage image-tube spectrograph at the 2.1 m (84-inch) reflector at Kitt Peak National Observatory. These galaxies constitute both components of 66 binary systems and one component of a further 4 systems. Duplicate spectra obtained for 12 galaxies were used to test the accuracy (or, at least, reproducibility) of the velocity determinations and the validity of the error estimates. The implied mean error in a <u>single</u> velocity determination is ~40 km s^{-1}.

These data were analyzed, with particular attention to the removal selection biases, by a procedure outlined below:

1) A maximum permitted difference in the radial velocities of the binary components is established. Pairs with larger velocity differences are rejected as spurious (i.e., projected, accidental pairs).
2) The ratio of M/L for early type galaxies to that for late types is estimated.
3) The radial velocity difference of each pair is scaled to that which would be expected for a pair of late-type galaxies with a fixed total luminosity.
4) The <u>observed</u> distribution of projected separations is convolved with the selection criteria to produce the <u>true</u> distribution of projected separations.
5) The distribution of 3-dimensional spatial separations is deduced from a power-law model fit to the true distribution of projected separations.
6) The fraction of systems with projected separations r_p which have spatial separations $r \gg r_p$ is calculated.
7) Several possible models for the orbital eccentricity of binary galaxies and for the distribution of mass within the individual galaxies are presented.
8) A set of radial velocity differences and projected separations is generated for each model, assuming that binary systems have fixed (but arbitrary) mass, separations distributed according to the power-law model, and a random spatial distribution. From these, a set of simulated observations are produced by the application of the selection criteria and the introduction of random "measurement" errors.

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9) In order to choose between the various models, a logarithmic-separation rank-sum test is used to compare the "shapes" of the joint distributions of radial velocity difference and projected separation for the observed and simulated data.

10) The best fit M/L and its uncertainty for each model are obtained from a standard rank-sum comparison of the distribution of a mass parameter in the observed and simulated data.

The various binary galaxy models are listed in Table I along with the derived mass-to-light ratios for late-type galaxies $\langle M/L \rangle_S$ and their uncertainties in Table II.

TABLE I

BINARY GALAXY MODELS

Model	Eccentricity	Mass	Comments
1	0	M'	circular orbit, point masses
2	1	M'	radial orbit, point masses
3	2/3	M'	average eccentricity, point masses
4	$\sqrt{5}/3$	M'	average axis ratio, point masses
5	P(e)de=2ede	M'	phase-space filling orbits, point masses
6	0	(r/10 kpc)M'	circular orbit, large massive halo
7	1	(r/10 kpc)M'	radial orbit, large massive halo
8	0	(r/10 kpc)M', $r \leq 100$ kpc 10 M', r>100 kpc	circular orbit small massive halo

A number of conclusions can be drawn (with varying degrees of certainty) from the analysis. These are listed below with comments:

1) The total mass-to-light ratio of late-type (i.e., spiral) galaxies in binary systems is quite large (perhaps ~65 $M_\odot/L_\odot$) compared to conventional rotation curve values (~5 $M_\odot/L_\odot$). This result extends the familiar "missing mass" problem for groups and clusters to binary systems. The indicated but rather less certain M/L for early-type (elliptical and SO) galaxies is twice as great (~130 $M_\odot/L_\odot$).

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TABLE II

BEST-FIT $\langle M/L \rangle_S$ AND ITS UNCERTAINTY

Model	Best $\langle M/L \rangle_S^*$	One σ Range	Three σ Range
1	33	26 - 43	15 - 74
2+	98	74 - 131	42 - 245
3	41	32 - 52	18 - 87
4	47	36 - 61	21 - 102
5+	48	36 - 62	21 - 108
6+	3.7	2.8 - 5.0	1.5 - 9.4
7+	10	8.5 - 16	3.6 - 34
8	6.4	4.8 - 8.6	2.8 - 16

*Total for models 1-5; 10 kpc value for models 6-8, (i.e., M'/L).

+Excluded by logarithmic-separation test.

2) This mass discrepancy can be understood if spiral galaxies possess dark halos of ~100 kpc radius containing ~10 times the disk mass. While the size and mass of these halos cannot be sharply determined by the present data, there is some evidence against halos larger than a few hundred kpc. Also halos with less than ~3 times the disk mass could not account for the full discrepancy. In view of other evidence, the heavy halo hypothesis seems to offer the best (but certainly not an exclusive) explanation of the data. Alternative explanations require one or more of the following: other (non-halo) sources of invisible mass, the existence of unbound and young (~10^9 yrs) binary systems, a non-velocity interpretation of redshifts, or an unconventional theory of dynamics.

3) The best model for the eccentricity of binary galaxy orbits lies between the extremes of e = 0 and e = 1; the latter is probably excluded by the data. Even a phase-space-filling distribution of orbits seems to have too many highly radial members. Unfortunately, moderate eccentricity orbits of galaxies with massive halos are too complex to model reliably. In any case, it is probably impossible to fully untangle the effects of orbital eccentricity and halo size with the present data and may prove difficult even with much more or better data.

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4) A proper analysis of binary galaxy data must take careful account of selection effects in the sample studied. This in turn requires that the sample be chosen using well-defined selection criteria. A neglect of these factors can lead to systematic errors of a factor $\gtrsim 10$ in the resulting M/L values. Earlier binary galaxy mass determinations probably suffered from such difficulties.

Future observational studies of binary galaxies may proceed in at least two ways. First, it will be possible to obtain more accurate radial velocities for much larger samples of binaries. Such data would allow better discrimination of the various possible orbital eccentricities (hence contraining $\langle M/L \rangle$) and might put interesting limits on the sizes and density distributions of the halos. A second possibility is that velocity maps (21 cm. or optical) of strongly interacting pairs could be obtained and compared to models such as those of the Toomres. In addition to checking the models, such a procedure might allow M/L to be determined for individual systems. Studies of such strongly interacting binaries should provide insight into more general problems associated with galaxy collisions.

REFERENCES

Turner, E.L. 1976a, Ap.J., **208**, No. 1, (in press).

__________ 1976b, Ap.J., **208**, No. 2, (in press).

__________ 1976c, Comm. on Astrph., (in press).

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DISCUSSION

G.A. TAMMANN: Could Drs. Kopylov and Turner explain in three words where they see the main reason for their disagreement. What magnitudes have they used?

I. KOPYLOV: Dr. Karachentsev believes that the Turner sample is still influenced by optical pairs. Indeed, Turner's sample is twice as small as Karachentsev's but only one pair of eight, recognized by Turner as optical, is in Karachentsev's sample. - The magnitudes are from Zwicky's catalogue, in a few cases they were estimated on the PSS prints.

E.L. TURNER: I have used Zwicky magnitudes with no absorption corrections. The difference between our results cannot be due to optical pairs in my sample because 1) they have been eliminated by application of a test of the Δv distribution; 2) the rank-sum test used to fit M/L values is not sensitive (as the usual $< \frac{\Delta v^2 r_p}{L} >$ method is) to a few anomalous pairs (i.e., the M/L value could not be changed by a large factor by elimination of any small fraction of the data); and 3) a separate analysis of a subset of the sample showing photographic evidence of tidal or other interactions yields very similar M/L values. In my view the difference is probably due to inadequate allowance for selection biases in his sample. The bias toward small angles between the separation vector and the line-of-sight may well be a critical one.

A.YAHIL: Let me first say that I think Turner ought to be congratulated for his model project, which was extremely well thought out and well executed. I would only like to take issue with him over one question of interpretation of his data. He concluded that his data were consistent either with standard size galaxies with high mass to light ratios, or with massive halos extending to about 100 kpc, but not more. Turner's result stems from his assumption of a fixed mass to light ratio. I would argue that the massive halo hypothesis, $M \sim r$, implies substantial invisible mass at large radii, and hence no close correlation between luminosity and total mass. Another way of putting this is the "isothermal picture" that Δv should not be correlated with r on any distance scale in Turner's sample, and not only up to 100 kpc.

I have tested Turner's primary sample for correlation between Δv and

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r, using non-parametric tests, and have found it to be insignificant. Perturbing Turner's data within observational errors resulted in correlation coefficients distributed as expected under the null-hypothesis of no correlation. Interestingly enough, the distribution of Δv was found to be Gaussian (cf. the investigation by Vidal and myself for groups and clusters of galaxies). After allowing for observational errors, the velocity dispersion per galaxy was found to be 130 km s^{-1} (185 kms^{-1} for a binary pair). I conclude that the data are consistent with the isothermal massive halo hypothesis on all distance scales surveyed. Of course, this does not rule out other models, such as conventionally sized, but massive galaxies.

Finally, let me comment that there is no doubt that Turner's binaries with $\Delta v < 500$ km s^{-1} are physically associated, as he has beautifully demonstrated by randomly mixing them. If we take the conventional view that the mass is concentrated where the light is, then the binaries must be bound, in view of the short crossing times. However, if there is substantial unseen matter, whose distribution can only be modelled, and which dominates the dynamics, then these systems need not be bound in the classical sense. Although they cannot be simply flying apart, they could expand in a more complex and slower manner.

E.L. TURNER: I essentially agree with Dr. Yahil's remarks. The binary galaxy data I have presented essentially imply $< M/L >_s \sim 50$ on scales of ~ 400 kpc. The issue of the size of the mass distribution (halos) is entangled with the distribution of semi-major axes and orbital eccentricities in a very complicated way. For example, point masses, e = 0 orbits, with a = constant give observed Δv increasing with increasing r_p ! I note in passing, that the assumption of constant M/L decreases the dispersion in the Δv - r_p plane.

H. ARP: The large M/L ratio you obtain for spirals disagrees with accepted M/L ratios. If we do not invoke "unseen" matter are you not forced to interpret some of your observed redshift differences as non-velocity.

E.L. TURNER: In the absence of material with M/L large compared to a "normal" stellar population, the binaries are either unbound (positive energy) systems or reflect non-Doppler redshifts.

H. ARP: But you argued that you did not have positive energy systems in your sample.

E.L. TURNER: Positive energies are mitigated against by the short crossing times.

J.-C. PECKER: Please do not apply in an automatic way the virial theorem either to groups or to couples: the universe is not that uniformly steady. The virial theorem has to be used with much more caution; couples and groups are often unstable, with positive energy!

E.L. TURNER: In my view, the virial theorem may be applied to any system (as a working hypothesis) if the crossing time $\Delta t \ll H_o^{-1}$, and there is no other evidence (colors, morphology, etc.) of small age or instability. This is certainly the case for the binaries.

G. DE VAUCOULEURS: Can Dr. Turner confirm from his data, in particular the Δv vs. r diagram, the conclusions of Zonn and Karachentsev (Acta Astron.) which contradicted the usual assumption of closed orbits?

I call your attention to the results of our paper read yesterday indicating that the residual velocity dispersion in the Local Group leaves little or no room for "missing mass", hence for "massive halos".

E.L. TURNER: If the relative velocity vectors between the pairs are closely aligned with the separation vectors (expected if $T/|W| \gg 1$), the predicted line-of-sight velocity difference declines rapidly with the projected separation independent of $T/|W|$. This rapid decline is not observed; this is the reason that the e = 1 models were rejected by the logarithmic-separation rank-sum test.

The mass (luminosity) weighted mean harmonic radius of the Local Group is decreasing (i.e., M31 is approaching us). This is the dynamically relevant fact, and it implies $M/L \sim 100$ (Gunn 1974, Comm. Astroph. and Sp. Sc., 6, 7.).

A. YAHIL: The discussion of the dynamics of the Local Group rests on several uncertain grounds. In particular, it depends on the rotation velocity assumed for the Sun.

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