THE MASS – METALLICITY – LUMINOSITY DENSITY RELATION FOR ELLIPTICAL GALAXIES

R. DE CARVALHO and S. DJORGOVSKI
Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, CA 91125

ABSTRACT Global properties of elliptical galaxies form a two-dimensional family. One aspect of this "fundamental plane" of ellipticals is a bivariate relation between the mass or luminosity, surface brightness or luminosity density, and a metallicity indicator (e.g., the Mg line strength index, or a color). In other words, there is a second parameter in the mass-metallicity relation, identified here as the luminosity density. The existence of this relation can be understood in the context of dissipative galaxy formation, reflecting both the effect of galactic winds, and an analog of the Schmidt law for star formation for proto-elliptical galaxies. Small, but systematic differences are found in the solutions for the field and for the cluster ellipticals, suggesting a systematic difference in their formative histories.

The global parameters of elliptical galaxies (e.g., mass, luminosity, density, metallicity, etc., but not the shape parameters, such as ellipticity) form a two-parameter statistical family. This can be represented by an inclined plane in the space defined, e.g., by radius, velocity dispersion, and mean surface brightness (Dressler *et al.* 1987; Djorgovski and Davis 1987, hereafter DD; Djorgovski 1987). The physical explanation behind this "fundamental plane" of early-type galaxies is that: (*a*) galaxies are bound by the Newtonian gravity; (*b*) they have a similar dynamical structure; and (*c*) the (M/L) ratio is a power-law function of the fundamental plane variables only (Faber *et al.* 1987; Djorgovski 1988; Djorgovski, de Carvalho, and Han 1988). The existence of this tight correlation implies an important regularity in the process of formation of elliptical galaxies.

We discovered a new family of distance indicator relations for elliptical galaxies, in which a distance-dependent quantity (radius or luminosity) is correlated with a linear combination of the mean surface brightness, and a metallicity term, e.g., a metallicity-sensitive color or the Mg index (de Carvalho & Djorgovski 1989). The new radius – metallicity indicator – surface brightness relations can be understood as a generalization of the fundamental plane: both the velocity dispersion and the final, average metallicity of an elliptical galaxy can be related to the escape velocity, and thus one can substitute a metallicity indicator in place of the velocity dispersion. A direct implication of the radius (or luminosity) – surface brightness – metallicity relation is that there is a "second parameter" in the mass-metallicity relation for elliptical galaxies, which we identify as the luminosity density.

Here we give explicit solutions for the bivariate relations between the virial mass (computed simply as $\sigma^2 R_e$, thus implicitely assuming that all galaxies have the same dynamical structure), mean luminosity density (computed as surface brightness / R_e), and metallicity indicators, viz., $(B - V)$ color and the Mg index. We use the data from the surface photometry by Djorgovski (1985; and DD), and the "7 Samurai" collaboration (Burstein *et al.* 1987). For galaxy distances we use the "Great Attractor" model by Lynden-Bell *et al.* (1988) and assume $H_0 = 100$ km s^{-1} Mpc^{-1} throughout.

We obtain the following scaling solutions for the DD sample, and the luminosity density in the Lick red (r_G) band:

All galaxies: $\log M = 4.65\,(B - V) - 0.68\, \log \rho_L +$ const.
Clusters: $\log M = 10.1\,(B - V) - 0.32\, \log \rho_L +$ const.
Field: $\log M = 2.9\,(B - V) - 0.81\, \log \rho_L +$ const.

All galaxies: $\log M = 8.4\, Mg - 0.61\, \log \rho_L +$ const.
Clusters: $\log M = 13.3\, Mg - 0.32\, \log \rho_L +$ const.
Field: $\log M = 6.8\, Mg - 0.81\, \log \rho_L +$ const.

For the 7S sample, and luminosity density in the B band, we obtain:

All galaxies: $\log M = 7.5\,(B - V) - 0.75\, \log \rho_L +$ const.
Clusters: $\log M = 8.5\,(B - V) - 0.9\, \log \rho_L +$ const.
Field: $\log M = 5.5\,(B - V) - 0.55\, \log \rho_L +$ const.

All galaxies: $\log M = 10\, Mg - 0.7\, \log \rho_L +$ const.
Clusters: $\log M = 11\, Mg - 0.75\, \log \rho_L +$ const.
Field: $\log M = 8\, Mg - 0.6\, \log \rho_L +$ const.

Note that some differences must exist on account of different bandpasses used, and the fact that the $(B - r)$ color should correlate with the metallicity. The errors of coefficients in these relations are of the order of 10%. In order to translate the metallicity indicators, the Mg index and the colors, into the metallicities, we compiled all available calibrations and population synthesis and analysis from the literature. The correspondence between these observables and the metallicity Z (or the [Fe/H]) is rather poorly understood. We adopt the following mean scaling relations:

$$\log Z \sim [\mathrm{Fe/H}] \sim (3.5 \pm 0.5)\, Mg$$

$$\log Z \sim [\mathrm{Fe/H}] \sim (3 \pm 1)\, (B - V)$$

Applying these conversions to the relations listed above, we derive the average scaling relations, with the higher weight given to the Mg index solutions. For the DD sample, in the Lick red (r_G) band we obtain:

All galaxies: $M \sim Z^{2.2\pm0.6} \rho_L^{-0.55\pm0.1}$, or $Z \sim M^{0.5\pm0.15} \rho_L^{0.3\pm0.1}$
Clusters: $M \sim Z^{3.7\pm0.6} \rho_L^{-0.38\pm0.06}$, or $Z \sim M^{0.27\pm0.05} \rho_L^{0.11\pm0.03}$

$$\text{Field:} \qquad M \sim Z^{1.7\pm0.6}\rho_L^{-0.65\pm0.15}, \quad \text{or} \quad Z \sim M^{0.65\pm0.15}\rho_L^{0.45\pm0.15}$$

For the 7S sample, in the B band, we obtain:

$$\begin{array}{llll}
\text{All galaxies:} & M \sim Z^{2.8\pm1.0}\rho_L^{-0.7\pm0.1}, & \text{or} & Z \sim M^{0.36\pm0.13}\rho_L^{0.25\pm0.12} \\
\text{Clusters:} & M \sim Z^{3.0\pm1.0}\rho_L^{-0.8\pm0.1}, & \text{or} & Z \sim M^{0.33\pm0.05}\rho_L^{0.27\pm0.12} \\
\text{Field:} & M \sim Z^{2.1\pm1.0}\rho_L^{-0.6\pm0.1}, & \text{or} & Z \sim M^{0.48\pm0.23}\rho_L^{0.28\pm0.16}
\end{array}$$

There is a fairly good agreement between the DD and 7S samples, even though they do not fully overlap, the data were obtained in different bands, using different instruments and techniques, and reduced independently. On the other hand, there are persistent systematic differences between the cluster and the field ellipticals, in the sense that the dependence of metallicity on the mass is steeper for the field galaxies. We are inclined to believe that this discrepancy is real, and that it reflects some systematic difference in the formative histories of field and cluster ellipticals, possibly the age effects.

These scaling laws should be explained by theoretical models of galaxy formation, such as those by Carlberg (1984). If the initial enrichment is regulated by galactic winds (energy input by the supernovæ), the final metallicity will depend on the escape velocity and thus the mass. The new term, luminosity density, implies an additional functional dependence at a fixed mass, similar to the Schmidt law for star formation. We note that the relations (especially for the cluster ellipticals) are fairly tight, and the residual scatter may be completely accounted for by the cumulative measurement errors.

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REFERENCES

Burstein, D., *et al.* 1987, Ap. J. Suppl., 64, 601.

Carlberg, R. 1984, Ap. J., 286, 416.

de Carvalho, R., and Djorgovski, S. 1989, Ap. J. Letters 341, L37.

Djorgovski, S. 1985, Ph.D. thesis, University of California, Berkeley.

Djorgovski, S., and Davis, M. 1987, Ap. J., 313, 59 (DD).

Djorgovski, S. 1988, in Starbursts and Galaxy Evolution, eds. Thuan, T. X. *et al.* , Moriond Workshop, p. 549. Gif sur Yvette: Editions Frontières.

Djorgovski, S. 1987, in IAU Symposium #127, Structure and Dynamics of Elliptical Galaxies, ed. T. de Zeeuw, p. 79. Dordrect: D. Reidel.

Djorgovski, S., de Carvalho, R., and Han, M.-S. 1988, in Extragalactic Distance Scale, eds. S. van den Bergh and C. Pritchet, A.S.P.Conf.Ser. 4, 329.

Dressler, A., *et al.* 1987, Ap. J., 313, 42.

Faber, S., *et al.* 1987, in Nearly Normal Galaxies, ed. S. Faber, p. 175. New York: Springer.

Lynden-Bell, D., *et al.* 1988, Ap. J., 326, 16.