ON THE MASS-LUMINOSITY RELATION FOR SPIRAL GALAXIES

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Received _

Revised _

N66 37562 (ACCESSION NUMBER) (THRU)

8 (PAGES) 1 (CODE)

CR-78384 (NASA CR OR TMX OR AD NUMBER) 30 (CATEGORY)

FACILITY FORM 602

ABSTRACT

The mass-luminosity relation for spiral and irregular galaxies found by Pskovskii and a similar relation between the mass of neutral hydrogen and the luminosity noted here lead to a relation between the total mass and the mass of neutral hydrogen for these galaxies. Several hypotheses have been advanced in order to understand this relation.

Poveda (1961) discovered that the dust-poor stellar systems obey a mass-luminosity relation, which has further been confirmed by Pskovskii (1965). If we denote by $\mathfrak{M}$ and $\mathcal{L}$ respectively the mass and the photographic luminosity of a galaxy, their relations can be written as

$$\mathcal{L} \propto \mathfrak{M}^{\alpha} \tag{1}$$

with $\alpha = 0.73$ from Poveda's study and $\alpha = 0.77$ from Pskovskii's study.

For spiral and irregular galaxies Pskovskii has found the relation (1) with $\alpha = 1.08$. This statistical relation was derived from empirical results of 13 galaxies whose total masses, $\mathfrak{M}$, have been determined directly plus another 13 galaxies of which only the masses $\mathfrak{M}_H$ of neutral hydrogen are known through the observations of the 21 cm. line. Since both the total masses and the masses of the neutral hydrogen in the first 13 galaxies have been determined, Pskovskii has reduced from them an empirical relation between the ratio $\mathfrak{M}_H / \mathfrak{M}$ and the photographic magnitude M_{pg} of the galaxy. From this relation, he is able to derive the total mass of each galaxy from the mass of its neutral hydrogen for the second 13 galaxies.

Pskovskii's procedure is legitimate, and his $\mathfrak{M}-\mathfrak{L}$ relation for spiral and irregular galaxies interesting, but we would like to take a different look at the problem. While the luminosity of a dust-poor stellar system is perhaps contributed by the red giant stars and stars on the horizontal branch in the H-R diagram, the dominant source of luminosity in a spiral or an irregular galaxy consists without doubt of the early-type and super-giant stars that are relatively young. In other words, the luminosity of the spiral system comes mainly from the stars that are recently formed out of the gaseous medium. If so, one would expect a relation between the mass of neutral hydrogen $\mathfrak{M}_H$ (instead of the total mass $\mathfrak{M}$) and the luminosity for these galaxies. Following this reasoning, we have plotted in Figure 1 the relation between $\mathfrak{M}_H$ and the photographic absolute magnitude M_{pg}

for 26 galaxies listed in Pskovskii's paper. The least-square solution which was obtained on the 7094 computer by Mr. Clarence Wade, Jr. at Goddard Space Flight Center, from the empirical points in the figure gives

$$\log \mathfrak{M}_H = 4.06 - 0.28\, M_{pg} \qquad (2)$$

which is represented by the straight line in the figure. It corresponds to relation (1) with $\alpha = 1.43$. If M_{pg} is solved in terms of $\log \mathfrak{M}_H$ in the least-square solution, we obtain $\alpha = 1.19$. Whichever α value we take, the relation thus found is now easy to interpret because the more neutral hydrogen a spiral or an irregular galaxy contains, the more bright young stars will be formed which increase the luminosity of the entire galaxy.

Actually the total luminosity $\mathcal{L}$ of a spiral or an irregular galaxy is composed of two sources: (1) $\mathcal{L}_a$ due to the young stars just emerging from gaseous media we have discussed, and (2) $\mathcal{L}_b$ due to the older stars (main-sequence stars of spectral type A and later, and population II giant stars). The luminosity arising from the first source is a function of $\mathfrak{M}_H$ while the luminosity arising from the second source has a dependence on $\mathfrak{M} - \mathfrak{M}_H$. If the photographic luminosity of these kinds of galaxies is indeed derived mainly from the first source, the result of $\alpha = 1.43$ in proportionality (1) indicates that the number of young stars prevalent at any time in the galaxy increases slightly faster than the mass of neutral hydrogen.

This shows in turn that the rate of formation of stars also increases faster than the gaseous matter available.

Presumably α may be related to the mode of star formation in the interstellar clouds. If stars are formed inside the cloud, α may be nearly equal to one. If, on the other hand, formation should be favorable at the boundary of two colliding clouds, perhaps α would be equal to two. Being between one and two the determined α value seems reasonable.

The fact that both $\mathfrak{M}-\mathcal{L}$ and $\mathfrak{M}_H-\mathcal{L}$ relations exist only shows that $\mathfrak{M}$ and $\mathfrak{M}_H$ are correlated. From the thirteen spiral galaxies whose $\mathfrak{M}$ and $\mathfrak{M}_H$ are known, we have found by the least square solution that

$$\log \mathfrak{M}_H = 1.55 + 0.74 \log \mathfrak{M} \qquad (3)$$

or $\mathfrak{M}_H \propto \mathfrak{M}^{0.74}$. Equations (2) and (3) lead to the relation obtained by Pskovskii.

The $\mathfrak{M}-\mathfrak{M}_H$ relation simply shows how neutral hydrogen has been depleted through the age by star formation in galaxies of different masses. We may offer three tentative hypotheses for the existence of this relation:

(1) A chance coincidence. For each galaxy $\mathfrak{M}_H$ at any time must depend in general upon the total mass and its age. It is a two-variable function. That $\mathfrak{M}_H$ is only a function of $\mathfrak{M}$ shows that it is a coincidence if the galaxies were not formed at the same time. As a result of the age difference the degree of compositeness (Morgan 1959) would be different

for different systems. The chance of this coincidence perhaps is very small.

(2) Formation of stars in the galaxy taking place mainly in the early stage. If so, the $\mathfrak{M} - \mathfrak{M}_H$ relation was the result of the initial batch of star formation. In the later stages the gas shed by evolving stars may roughly balance its depletion through star formation. In other words, $\mathfrak{M}_H$ in each galaxy is roughly in a state of equilibrium and the $\mathfrak{M} - \mathfrak{M}_H$ relation will be only slightly modified as time goes on. Consequently even though the galaxies may be formed at different times, the same $\mathfrak{M} - \mathfrak{M}_H$ relation will persist at any time. Also the $\mathfrak{M}_H - \mathcal{L}$ relation will not change greatly with time.

(3) Stars forming gradually in each galaxy but all galaxies formed at about the same time. In such a case there will be a $\mathfrak{M} - \mathfrak{M}_H$ relation at any given time but the form of this relation changes with time. Whether the $\mathfrak{M}_H - \mathcal{L}$ relation will remain the same depends upon the manner in which the rate of star formation varies with the decreasing $\mathfrak{M}_H$.

If either hypothesis (2) or (3) turns out to be correct, it appears that star formation in the spiral or irregular galaxies at any time depends dominantly only upon $\mathfrak{M}_H$ and perhaps also $\mathfrak{M}$. It follows that the morphological sequence of galaxies according to the standard classification must result from some parameters, such as the angular momentum per unit mass, etc., which do not play a determining effect on star formation. We may also conclude that the spiral (or irregular) galaxy and the elliptical galaxy are not genetically related, namely they do not form an evolutionary sequence, because none of the spiral (or irregular) galaxies in the mass range considered has exhausted its neutral hydrogen while many elliptical galaxies exist in that same mass range.

The ratio $\mathfrak{M}_H/\mathfrak{M}$ decreases with $\mathfrak{M}$. This would show that the proportion of $\mathfrak{M}_H$ with respect to the total mass decreases more rapidly with time in more massive galaxies than less massive ones. Such a suggestion is consistent with $\alpha > 1$ in the $\mathfrak{M}_H - \mathcal{L}$ relation obtained previously.

Both hypotheses (2) and (3) represent idealized cases. Actually, perhaps there is a high rate of star formation in the beginning which determines the initial $\mathfrak{M} - \mathfrak{M}_H$ relation. But in the late stages star formation continuously depletes $\mathfrak{M}_H$ at an appreciable rate. Consequently the $\mathfrak{M} - \mathfrak{M}_H$ relation is significantly, though perhaps not drastically, modified. If the galaxies were formed at different times, this would produce a scatter of points from the $\mathfrak{M} - \mathfrak{M}_H$ relation.

Finally it is a pleasure to acknowledge my sincere thanks to Drs. D. N. Limber, D. E. Osterbrock, and A. Poveda for valuable discussions and communications, and to Mr. Clarence Wade, Jr. for obtaining the least-square solutions on the IBM computer at Goddard Space Flight Center. A part of this investigation is supported by National Aeronautics and Space Administration under a research grant.

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Legend

Fig. 1 - An empirical relation between the mass of neutral hydrogen $\mathfrak{M}_H$ and the photographic absolute magnitude for spiral galaxies. The solid line that represents equation (2) in the text was derived from the 26 empirical points shown in the figure.