TULLY-FISHER RELATION

The **Tully-Fisher Relation**

$$L \propto W^{\alpha}$$

is a correlation that holds for galaxies with disks stabilized by rotation, between the intrinsic luminosity L of the galaxy in optical or near-infrared bands and the rate of rotation W .

History

In 1922, Ernst Opik determined a distance to the Andromeda galaxy using the virial theorem [1]. A self-gravitating system will obey the law

$$M = kW^2R/G$$

where M is the mass, W , with units of speed is a characterization of the motions in the body, dominated by rotation in the case of a disk galaxy, R is a measure of the linear size, G is the universal gravitational constant, and k is a dimensionless constant of order unity that depends on the geometry of the system. The line-of-sight component of velocities are observable from measurements of the Doppler shift on the width of emission or absorption lines, and deprojected values can be inferred from models. The dimension can be separated into an observable angular part θ and the distance d , $R \propto \theta d$. Opik took a dependence of the mass $M \propto (M/L)\ell d^2$. Here M/L is the mass-to-light ratio and was assumed to have a value of typical stellar systems. The intrinsic luminosity $L \propto \ell d^2$ depends on the observed brightness ℓ and distance d . Opik used observed information about W , θ , and ℓ and assumptions about M/L and the geometry of the system to calculate a distance d=450 kiloparsecs. It is generally said that the astronomical community became convinced that galaxies are distinct from our Milky Way in 1925 with Edwin Hubble's observations of Cepheid variables in the Andromeda galaxy which gave a distance of 285 kiloparsecs. The modern value is 780 kiloparsecs. Opik's measurement was earlier and closer to the correct value, although Hubble had the greater influence. The virial theorem continued to be used to determine distances into the 1970s with what was usually called the "indicative mass" method. It was stripped down to the form $L \propto W^2R$. Tully and Fisher [2] suggested the use of two alternatives

$$L \propto W^{\alpha}$$

$$L \propto R^{\beta}$$

These alternatives reduce the number of variables from 3 to 2 and allow departures from the virial theorem. The first form has the attraction that only one parameter depends on distance. This equation became known as the Tully-Fisher relation.

The motivation for the development of the relationship was based on well founded physics: more massive galaxies would be both more luminous and rotate faster. It was appreciated that there was a lot of leverage for the measurement of distances because of the d^2 dependence of observed luminosity. However the small scatter and apparent universality of the relationship could not have been fully anticipated. These properties have made the relationship interesting not only for the determination of distances but also as a constraint on models of the formation and evolution of galaxies. In particular, note that Opik's derivation of the virial relation above assumes a universal value for the mass-to-light ratio, M/L . Given the dominance of dark matter in spiral galaxies, it is not at all obvious that there would be a universal relationship between mass and light. The fact that the Tully-Fisher relation has as little scatter as it does is an important clue regarding the connection between the luminous and non-luminous components of spirals.

Properties

A version of the relationship is seen in Figure 1 which plots absolute magnitudes in the I band centered at 820 nm vs. the logarithm of the Doppler width of the 21 cm radio line (in km/s) corrected for inclination. The amplitude of the linewidth is approximately twice the maximum rotation velocity since the linewidth includes components of the motion toward and away from the viewer. The small symbols of various shapes and colors represent galaxies drawn from 5 separate clusters of galaxies and the large open symbols represent nearby galaxies with accurate independently known distances. The straight line is a regression to the data with errors in linewidth. The 5 cluster sample defines the slope and the galaxies with independently known distances define the zero point.

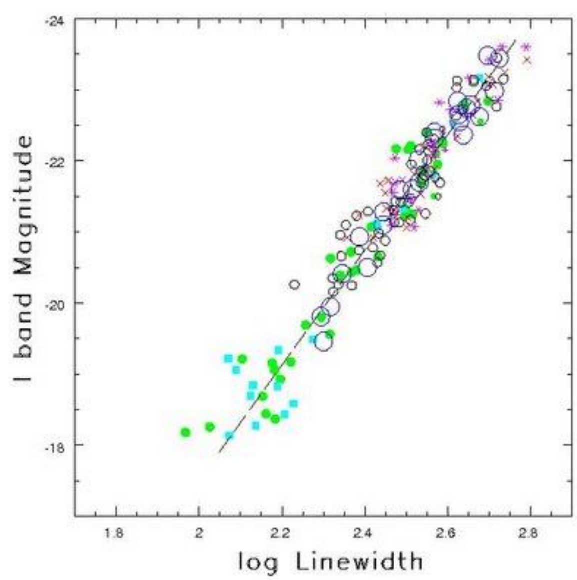

Figure 1: The Tully-Fisher relation

Here are some of the properties of the relationship.

- The scatter diminishes toward near-infrared passbands. It may slightly degrade at passbands beyond 1 micron although that may only be a consequence of competition from airglow, reducing the accuracy of the galaxy photometry.
- The relationship holds for disk dominated systems. It seriously breaks down for S0 types, with greatly increased scatter and a zero point offset. A few percent of disk systems are strongly deviant, especially those affected by strong starbursts or mergers.
- At optimal passbands between 600 nm and 800 nm, the scatter is ~0.35 magnitudes, equivalent to 17% uncertainty in distance. Observational uncertainties enter into measurements of apparent luminosity, including adjustments for internal dust obscuration, inclinations, and the estimator of galactic rotation. It is possible that most of the scatter arises from observational uncertainties and the intrinsic scatter is much less than the observed scatter.
- The power law relationship has been observed to break at low luminosities but this might only be because much of the baryonic mass in low mass galaxies is in gas rather than stars. Recipes convert luminosity into the mass in stars, then the sum of this mass and the mass observed in cold gas gives a parameter called the "baryonic mass". In plots of baryonic mass vs. rotation velocity, a power law holds over 5 decades in mass [3].
- The slope of the Tully-Fisher relation depends on passband, steepening from the blue toward the infrared. In the relation $L \propto W^{\alpha}$, α ranges from 3 to 4. Details depend on how luminosities and the rotation parameter are defined and how the regression that gives the slope is carried out.
- Attempts to reduce scatter with added parameters have been unconvincing. There is weak evidence for a surface brightness dependency.

The relationship for disk galaxies is paralleled by the Faber-Jackson relation [4] for elliptical galaxies

$$L \propto \sigma^{\gamma}$$

where σ is the velocity dispersion measured at the center of the system. The Faber-Jackson relation has a somewhat larger scatter but in this case surface brightness as a third parameter significantly improves the correlation. The result is a formulation called the "fundamental plane" [5,6]. It is interesting that the fundamental plane transforms considerably more closely into the virial theorem than the Tully-Fisher relation. Further elaboration splits according to whether the interest is the tool for measuring distance, or the observational constraints on galaxy evolution since $z \sim 1$, or the efforts made to reproduce the relationship with galaxy formation models.

Distance Measurements

In the 1970s the situation regarding the extragalactic distance scale was in a sorry state. The characterization of this scale, the Hubble constant $H_0=<V_i/d_i>$ is the ratio of the cosmic expansion velocity to the distance from us averaged over a fair sample of targets. There was a debate over the value of this constant at the level of a factor two. At its core was a critical issue. The standard cosmological model at the time held that the primary constituents of the universe were particles of matter that had been acting since the Big Bang to slow the cosmic expansion. The "theory of inflation" anticipated that the density of matter amounted to the "critical value" required to give a flat topology. This model implies a specific link between the age of the universe and the expansion scale. The age of the universe was reasonably constrained by the age-dating of stellar populations in globular clusters. The theoretically preferred model required that the Hubble constant be at the very lowest of the range being seriously discussed at the end of the 20th Century. If H_0 lay in the mid to upper range then the theorist's preferred model was excluded.

For some 20 years after its inception, the Tully-Fisher relation was generally considered to give the best distances to galaxies in the range required to define H_0 . There was controversy [7,8]. Other methodologies emerged, such as the use of the bright end cutoff in the luminosities of planetary nebulae [9] and "surface brightness fluctuations" caused by the distribution of the brightest stars in galaxies dominated by old populations [10]. There was a general, but not unanimous, agreement among specialist observers that H_0 was being measured at a value that precluded the standard model.

A paradigm shift came with the evidence from observations of supernovae of type Ia that the universe appears to be accelerating [11,12]. It seems that a repulsive dark energy is dynamically dominant. The relationship between ages and expansion rate is altered. H_0 is now compatible with the new preferred model.

New methods to measure distance become available. The use of supernovae is particularly accurate. If the brightest red giant branch stars are resolved in the image of a galaxy, the known luminosities of these stars gives a good distance [13]. However each of the various methods has a weakness: targets arise serendipitously, or only include certain types of galaxies, or are required to be very nearby. There is still an important role for the Tully-Fisher relation. It is no longer the most accurate method on a single case basis but since the application is to normal disk systems, with little restriction in range, it enables the determination of distances to many thousands of galaxies in all the environments that galaxies are found [14,15].

Independent of the value of the Hubble Constant, the Tully-Fisher relation can be used to measure peculiar velocities, motions of galaxies that are deviations from the linear Hubble expansion. These motions are thought to be due to the gravitational influence of over- and under-densities of matter. There is an extensive literature discussing the relationship between the peculiar velocities of galaxies measured via the Tully-Fisher relation and the large-scale distribution of galaxies.

Constraints on Galaxy Evolution

The other uses of the Tully-Fisher relation derive from the constraints imposed on ideas of galaxy formation. Although the general correlation between luminosity and rotation rate was anticipated, it was a surprise to find it to be so tight, with so little spread caused by additional parameters. The dependence need not have been a power law. What defines the slope? It is somewhat different from what the virial theorem would give and what is seen with bulge dominated systems. Especially, although there is an obvious linkage between the luminosity in stars and the stellar mass, why is the correlation so tight if most of the mass is non-baryonic?

An empirical approach to these issues finds investigators pursuing the challenging task of observing spiral galaxies at large redshifts in order to look for the effects of evolution. This is difficult because the galaxies are faint, and have an angular size not much larger than the typical seeing at modern telescopes. Galaxies with given rotation properties, thought to be specified by the mass of the host halos, were brighter at earlier epochs. However a correlation very similar to that seen today between luminosity and rotation rate was already in place when the universe was only half its present age [16].

Attempts to understand the detailed physical basis for the Tully-Fisher relation date from shortly after the discovery of the correlation. The roughly $L \propto W^4$ dependence found in the infrared is consistent with the virial theorem if the mass in galaxies accumulates with a universal central surface density, radial distributions are self-similar except for scalelengths, and there is a fixed relationship with light [17]. The situation is evidently more complicated, but the general properties of the relationship emerge from hierarchical clustering models of galaxy formation [18]. The very small scatter seems to require feedback processes that control the partition of angular momentum between baryons and dark matter [19]. In the details, there are strong constraints on the transformation of gas into stars over the spectrum of galactic halo masses [20].

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