The Baryon Fraction Distribution
and the Tully-Fisher Relation

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Abstract. A number of observations strongly suggest that the baryon
fraction is not a universal constant. One obvious interpretation is that
there is some distribution of $f_b$, and the different observations sample
different portions of the distribution. However, the small intrinsic scatter
in the Tully-Fisher relation requires that the baryon fraction be very
nearly universal. It is not easy to resolve this paradox in the framework
of the standard picture.

1. The Baryon Fraction Must Vary

There now exist a number of observations which indicate that the ratio of lu-
minous to dark mass is not the same for all systems. Rather than the single
universal baryon fraction that we have nominally assumed, $f_b$ seems to have a
broad distribution. Some of the observations suggesting this situation include
satellite galaxies, tidal tails, X-ray clusters of galaxies, and low surface brightness
galaxies.

The satellite studies of Zaritsky et al. (1994, 1997) imply that the halos of
$L^*$ galaxies are very large and massive. On the other hand, the morphology of
tidal tails is very difficult to reproduce unless the mass of halos does not exceed
the disk mass by more than a factor of 10 (Dubinski et al. 1996). This result is
inconsistent with the satellites result by a factor of $\sim 2$. One might be tempted
to equivocate at this level, but the result should not be lightly dismissed (Mihos
et al. 1997).

The baryon fraction is directly estimated in X-ray clusters (White et al.
1993; Evrard et al. 1996). These indicate $f_b \sim 0.1$ with significant (factor of
two) scatter which is argued to be real (White & Fabian 1995). In contrast, a
stringent limit is placed by the rotation curves of the most dark matter dom-
inated galaxies: $f_b < 0.05$ (de Blok & McGaugh 1997). This is not really
consistent with the cluster result, and attempting to fit the rotation curves with
NFW halos (Navarro et al. 1996) requires even lower baryon fractions of 0.01
– 0.02. This differs from clusters by nearly an order of magnitude, and is very
difficult to explain away. Mass expulsion of baryons is often invoked, but this
scenario predicts that the gas should be swept away. The actual galaxies are in fact quite gas rich. Other explanations could be offered, but most are rather hand-waving and lack predictive power.

Another approach is to suppose that there is a distribution of baryon fractions. The apparently contradictory observations might then be reconciled: they simply happen to sample different portions of the distribution. However, this apparently reasonable approach has a serious problem in explaining the Tully-Fisher relation.

2. The Baryon Fraction Must Not Vary

The traditional explanation of the Tully-Fisher relation supposes that light is proportional to mass: \( L \sim M \). This works if, among other conditions, there is a universal baryon fraction. Any distribution in the baryon fraction should be reflected in the intrinsic scatter of the relation. The small observed scatter directly implies a narrow \( f_b \) distribution. This restriction applies to all galaxies which fall on the Tully-Fisher relation: both the central galaxies of the satellite studies and low surface brightness galaxies, and presumably the progenitors of tidal tail systems as well.

We can quantify this limit by supposing that the Tully-Fisher relation

\[
L \sim V^x
\]

arises from an underlying relation of the form

\[
M \sim V^y.
\]

Presumably, \( 3 < x \approx y < 4 \). Note that some rather gross assumptions go into equation 2, and fine-tuning problems involving the surface brightness or scale length are unavoidable (Zwaan et al. 1995; McGaugh & de Blok 1998).

Luminosity can be directly related to mass by

\[
M = \frac{\Upsilon_* L}{f_* f_b}
\]

where \( \Upsilon_* \) is the mass-to-light ratio of the stars, \( f_* \) is the fraction of baryonic mass in the form of stars, and \( f_b \) is the baryon fraction. It follows that

\[
\frac{\Upsilon_*}{f_* f_b} \sim V^{y-x}.
\]

By construction, the quantity \(|y - x|\) must be small, \(|y - x| < 1\).

For the moment, let us assume that \( \Upsilon_* \) and \( f_* \) are finite but small contributors to the scatter in the Tully-Fisher relation. Even if the \( f_b \) distribution dominates the scatter,

\[
\frac{\delta f_b}{f_b} < |y - x| \frac{\delta V}{V}.
\]

The intrinsic scatter in the Tully-Fisher relation tightly constrains the allowed range of \( f_b \). For a generous assumptions of \(|y - x| = 1\) and an intrinsic scatter of 0.5 mag.,

\[
\frac{\delta f_b}{f_b} < 0.12.
\]
This is very small. Moreover, we have ignored the scatter in $\Upsilon_* \text{ and } f_*$. From the perspective of stellar populations, one expects some scatter in $\Upsilon_*$. Variation in $f_*$ is directly observed (McGaugh & de Blok 1997). This further tightens the constraint on the baryon fraction distribution. This constraint specifically applies to the objects discussed above where a factor of 2 or more variation was inferred, excepting only clusters of galaxies.

This is a serious problem with no clear solution.

3. The Slope of the Tully-Fisher Relation

We can also place limits on the amount by which the slope of the observed Tully-Fisher Relation is allowed to vary from the underlying mass-velocity relation. Let us assume simply that the various components are a function of luminosity: $\Upsilon_* \sim L^a$, $f_* \sim L^b$, and $f_b \sim L^c$. By equation 4, these slopes are related by

$$a - b - c = y - x.$$  \hspace{1cm} (7)

A reasonable limit is $|a - b - c| < 1$, and probably rather less.

Given that brighter galaxies tend to be redder, the stellar mass-to-light ratio is probably a weakly increasing function of $L$: $a > 0$, with its precise value depending on bandpass. The stellar mass fraction $f_*$ is observed to increase with luminosity roughly as $b \sim 0.2$ (McGaugh & de Blok 1997). The two tend to offset one another, so they should cause only a mild deviation of the observed slope from the intrinsic one as long as $a \sim b$. The usual assumption $L \sim M$ thus seems well justified as long as the baryon fraction is a universal constant. If this is not the case, any systematic variation of $f_b$ with luminosity feeds directly into the slope. Since the observed slope is near to a reasonable intrinsic value (Tully & Verheijen 1997), this also argues against substantial variation in $f_b$.

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