Hubble Deep Fever: A faint galaxy diagnosis

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Abstract. The longstanding faint blue galaxy problem is gradually subsiding as a result of technological advancement, most notably from high-resolution Hubble Space Telescope imaging. In particular two categorical facts have recently been established, these are:

1) The excess faint blue galaxies are of irregular morphologies, and,

2) the majority of these irregulars occur at redshifts \( 1 < z < 2 \).

These conclusions are based on the powerful combination of morphological and photometric redshift data for all galaxies in the Hubble Deep Field to \( I < 26 \). Our interpretation is that the faint blue galaxy excess, which incidentally coincides with the peak in the observed mean galaxy star formation rate, represents the final formation epoch of the familiar spiral galaxy population. This conclusion is corroborated by the low abundance of normal spirals at \( z > 2 \). Taking these facts together we favour a scenario where the faint blue excess is primarily due to the formation epoch of spiral systems via merging at redshifts \( 1 < z < 2 \). The final interpretation now awaits refinements in our understanding of the local galaxy population.

1 Introduction

The faint blue galaxy problem has been with us for several decades and is comprehensively reviewed in Koo & Kron (1992) and Ellis (1997). The problem is surmised as: an observed excess of faint galaxies over the zero or passive evolution model predictions. This excess first arises at \( b_J = 22 \) mags and extends to the faintest magnitudes probed (\( b_J = 28.5 \) mags, c.f. Metcalfe et al. 1995). The problem is compounded when one also considers the redshift distributions of galaxies at \( b_J = 22 - 24 \) mags, e.g. Glazebrook et al. (1995a), which in shape agree well with the zero-to-passive model predictions, but of course not in amplitude (i.e. a reiteration of the original faint blue galaxy problem). Spectroscopic surveys to fainter magnitudes are currently limited by aperture and signal-to-noise considerations. The unfortunate situation then, is that the models require a continuous renormalisation to match the observations and such a solution often results in contrived and implausible physical implications. In this overview I summarise the recent substantial developments in the observational data from Hubble Space Telescope imaging and in particular the Hubble Deep Field (HDF), the current interpretation and finally the future observations required. The expectation is that through these refinements, as opposed to speculative retro-fitting, comes concordance.
2 Hubble Deep Field Imaging

The past three years have seen two large strides forward into new parameter space within this field, these are: the ability to discern morphologies (c.f. Ode- wahn et al. 1995) and the ability to reliably estimate redshifts/distances (c.f. Fernández-Soto, these proceedings; Hogg et al. 1998). Even more powerful however, is the combination of these two approaches and the generation of morphological number-count $N(m,T)$, AND morphological redshift distributions $N(z,T)$, to $I < 26$ (c.f. Driver et al. 1998). Figures 1 and 2 are adapted from Driver et al. and show the latest comparison between faint galaxy observations and models.

Before comparing the observations with the models it is first worth highlighting a number of purely observational points:

1. At bright magnitudes the total counts are dominated by the classical Hubble types (i.e. ellipticals and spirals).
2. The elliptical galaxy counts are almost totally flat at faint magnitudes and eventually contribute negligibly to the total galaxy counts.
3. The galaxy counts of disk and irregular systems are steep and almost linear over a broad magnitude range, with no sign of flattening and with gradients of $\sim 0.3$ and $\sim 0.4$ respectively.
4. At faint magnitudes the counts are divided almost equally between disks and irregulars over a broad magnitude range.
5. All redshift distributions become broad towards fainter magnitudes and the Euclidean correlation between faintness and distance breaks down entirely.
6. Few spiral systems are seen at $z > 2$.
7. The late-type/irregular distributions are the broadest but typically have a higher mean redshift then either of the so called “giant” classes.

At this point it is important to note that the data presented in these Figures is only feasible from a space borne imaging system, such as that onboard the Hubble Space Telescope. Plate 1 shows a qualitative true colour representation of this same dataset subdivided into redshift intervals and arranged according to apparent magnitude within these redshift intervals (and therefore crudely absolute magnitude). Note that no correction can/has been made for the K-correction in this plate. The plate essentially provides a good sanity check on the data quality and believability of the quantitative results presented in Figures 1 and 2. The trend toward higher irregularity at $z > 1.5$ is irrefutable and the degree of irregularity is far higher than that seen in the limited UV observations of local normal galaxies - i.e. the first indication is that the increase in irregularity towards higher-z is intrinsic rather than a manifestation of the shifting bandpass.

3 Faint Galaxy Modeling

The models shown on Figures 1 and 2 are described in detail in Driver et al. (1998) and are based on the following: Local morphological luminosity functions
from the CfA survey (c.f. Marzke et al. 1994); a standard flat cosmology; zero or passive E- and K- corrections (c.f. Poggianti); and a global renormalisation at $b_J = 18$. By comparison with Figure 1 we see that the ellipticals are consistent with zero-evolution, spirals with passive-evolution and irregulars require strong-evolution. These form the basic conclusions derived in a number of previous papers based on morphological galaxy counts alone (e.g. Driver et al. 1995; Glazebrook et al. 1995b) and independently from the Canada France Redshift Survey (c.f. Lilly et al. 1995). This interpretation has the obvious result that the level of evolution correlates with the mean local colour of the respective galaxy sub-class, i.e. the systems with the oldest stellar populations require the least evolution and vica-versa. However with the inclusion of photometric redshift data (described in Fernández-Soto, these proceedings) we can now take the comparison between observations and models one step further and, immediately, we see from Figure 2 that the description above is overly simplistic. Considering each class independently:

The ellipticals’ $N(z,T=E/S0)$s are well embraced by the zero-to-passive evolution $N(z)$ models (bear in mind the strong clustering nature of ellipticals and the limiting statistics in this single sight-line). However, there is a tendency towards an underdensity of ellipticals in the faintest magnitude intervals suggesting some moderate obscuration, disassembly or transmorphing. Although taking into consideration the fact that the observed $N(z,T=E/S0)$ distribution is broad and not obviously truncated argues against a homogeneous evolutionary path (i.e. no single epoch of formation!) and leads us to ask whether this population is formed via a continuous ongoing crystallisation out of a non-elliptical
Fig. 2. Redshift distributions for: (a) all galaxies, (b) ellipticals, (c) spirals and (d) irregulars) for progressively fainter magnitude intervals. The models lines show the zero- (solid) and maximal passive- (broken) evolution models based on a global renormalisation at $b_J = 18$. 
population. Given the limited statistics for this population more observations are required. A simpler interpretation is to simply adopt a lower normalisation for the elliptical models.

For the spirals we see that passive-evolution models match both the counts and the brightest $N(z)$ distribution. However, disparity creeps into the plots at fainter magnitude intervals. In fact there is a repetition of the original faint blue galaxy problem within this sub-class in the sense that the observations agree in form to the zero-evolution models but are discrepant in amplitude. There are three obvious possibilities: (1) spiral galaxies undergo zero-evolution and exhibit a steeper local luminosity function than that derived from the CfA; (2) spiral galaxies have disassembled into a number of similar luminosity but less massive disk systems and (3) luminosity-dependence evolution. A frequent criticism leveled against morphological classification at faint magnitudes is the concern that regular galaxies simply appear more asymmetrical due to the K-correction i.e. objects viewed in the UV are intrinsically more irregular (e.g. Giavalisco et al. 1996). This is a valid concern but there are two points worth noting: Firstly, from Plate 1 the irregulars at $z > 1.5$ are extremely irregular and secondly, even with the potential for mis-classification we still see too many spirals at lower redshifts implying substantial number evolution ($\times 2$).

For the irregulars we saw from Figure 1, that even with the contentiously steep CfA local luminosity function, extremely strong evolution would be required before the model $N(m,T=SD/Irr)$ matches the observations. However the $N(z,T=SD/Irr)$s of Figure 2 make this a moot point, and it is clear that the irregular class is irreconcilable with the observed $N(z,T=SD/Irr)$ distribution. The implication is that more than one population/process is contributing to the class of irregular galaxies: e.g. true irregulars — typically low-luminosity; and transient irregulars — peaking in the interval $z = 1 - 2$. Further work will be required to subdivide this population, however, before the nails are banged home in the dwarf-dominated coffin, we note that at no point does the $N(z,T=SD/Irr)$ model strongly over predict the observed distribution. Hence a steeply rising local luminosity function, akin to that seen in the CfA survey, is fully consistent and arguably favored by the low redshift end of the irregular $N(z)$ distribution. However it is fair to say that the dwarf galaxy contribution to the faint galaxy counts is a minority component of the faint blue galaxy excess ($< 20\%$ to $I < 26$).

Finally we must also consider a more holistic interpretation allowing freedom of movement from one class to another. At some point all objects derive from some primordial density distribution and the distinction between morphological classes must eventually dissolve. Considering the extreme distances over which the HDF objects in this dataset are being seen this is clearly a serious consideration. One interesting coincidence from Figure 2, is that the high-z irregulars are typically observed, within each magnitude interval, at a redshift slightly higher to the spiral population. This begs the question as to whether this population represents the spiral progenitor population (non-relaxed spirals)! In fact one might argue to simply combine the spiral and irregular sub-classes in which case the overall
form of the \(N(m,T=\text{disk})\) distributions agree well with the models and we are simply left with a disk normalisation problem.

4 What next?

A few things prevent a definitive description and these are almost all due to uncertainties in our understanding of the local galaxy populations. The most important step forward over the next decade is to refocus our attention on re-defining local galaxy samples and this has been recognised by the implementation of the 2dF and SLOAN surveys. However as has been shown here the inclusion of morphologies is crucial and both of these surveys need to find a way to incorporate such information. Accurate consensus of the local morphological luminosity functions and their precise normalisation would represent the single most important advancement. In fact it is the normalisation problem, not discussed here but see Shanks (1989), at \(b_J = 18\), which stymies our attempts at a definitive explanation. The models shown here have been normalised uniformly to the total counts at \(b_J = 18.0\), which in the absence of morphological data is an arbitrary decision taken to minimise the number of free parameters. If we allow ourselves the luxury of independent morphological renormalisations then we might adopt a renormalisation ratio of 1:2:3 for E/S0:Sabc:Sd/Irrs respectively. Such a normalisation goes a long way to simplifying the current interpretation outlined in the previous section. If the reason for the local normalisation problem is due to surface brightness selection effects as has been postulated then such a renormalisation would be favoured. Once again we see that we require local morphological information at brighter rather than fainter magnitudes (where morphological distinctions are expected to evaporate). How ironic it is then, that we now know more about the statistical properties of the distant galaxy population than that of the local population.

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References

Driver S.P., Windhorst R.A., Ostrander E.J., Keel W.C., Griffiths R.E., & Ratnatunga K.U., 1995, ApJL, 449, L23
Driver S.P., Windhorst R.A., Phillipps S., & Bristow P., 1996, ApJ, 461, 525
Ellis R.S., 1998, ARA&A, 35, 389
Glazebrook K., Ellis R.S., Colless M., Broadhurst T., Allington-Smith J., & Tanvir N., 1995a, MNRAS, 273, 157
Glazebrook K., Ellis R.S., Santiago B., & Griffiths R.E., 1995b, MNRAS, 275, L19
Giavalisco M., Bohlin R.C., Macchetto F.D., & Stecher T.P., 1996, AJ, 112, 369
Hogg D., et al., 1998, ApJ, in press
Koo D.C., & Kron R.G., 1992, ARA&A, 30, 613
Lilly S.J., Le Fervre O., Hammer F., Crampton D., 1996, ApJ, 460, 1
Marzke R.O., Geller M.J., Huchra J.P., & Corwin H.G., Jr., 1994, AJ, 108, 437
Metcalfe N., Shanks T., Fong R., & Roche N., 1995, MNRAS, 273, 257

Odewahn S.C., Windhorst R.A., Keel W.C., Driver S.P., 1996, ApJL, 472, L13

Poggianti B.M., 1997, A&AS, 122, 399

Shanks T., 1989, in proc *The Extragalactic Background Light*, eds Bowyer S.C., Leinert C., (Publ: Kluwer Academic Press), 269
Fig. 3. A colour montage of all galaxies in the Hubble Deep Field with $I < 26$, the galaxies are subdivided into redshift intervals as indicated and according to apparent magnitude within each redshift interval. Note the increase in irregularity towards both faint magnitudes (true irregulars) and high redshift (evolutionary irregulars). The increase in irregularity at $z > 1.5$ coincides with the widely discussed “Madau peak”.