THE REDSHIFT DEPENDENCE OF GALAXY SURFACE BRIGHTNESS

Philippe Crane

European Southern Observatory

Geneva, Switzerland

and

Alan W. Hoffman

Dept. of Physics and Astronomy

University of Rochester

Rochester, New York

Nous avons déterminé la brillance superficielle moyenne d'amas à l'intérieur d'un diamètre linéaire projeté de 20.3 kpc en faisant la photométrie de galaxies dans six amas ayant un redshift de z=0.05 à 0.20. Pour toutes les cosmologies dans lesquelles le décalage vers le rouge est uniquement dû à l'expansion, la brillance superficielle devrait avoir la forme m (SB)=2.5 a log (1+z) + b où a≡4 et b est une constante d'échelle. Nous trouvons a=4.1 ± 1.6 et b= 22.12 ± 0.21. Ces résultats supportent fortement l'interprétation des décalages vers le rouge comme dus à l'expansion de l'univers.

A cosmological model independent connection between the expansion of the Universe and observed redshifts (z) can be demonstrated if the $(1+z)^{-4}$ dependence of the surface brightness (SB) of some class of standard objects is established. The functional form $SB(z) = SB_o/(1 + z)^4$ follows from the Liouville theorem in a 4-dimensional expanding space-time (Misner, Thorne, and Wheeler, 1973)

and is, hence, based on some of our most fundamental physical
concepts. Apart from evolutionary effects and the like,
significant departures from this predicted form would have
major consequences for our understanding of the cosmos in
terms of locally derived physics.

The major problem with any attempt to measure this
surface brightness is to find standard objects properly
distributed in space. Ideally one would like to use a set
of galaxies for which an intrinsic physical length can be
determined from the galaxies themselves. The luminosity
within this physical length can then be used to determine an
average SB. However, even this ideal procedure requires the
observation of many galaxies at each redshift since there
exist no true standard galaxies (Crane, 1976). Ground based
attempts to follow this procedure will most certainly be
frustrated by the fact that the best intrinsic physical
length, the galaxy core radius (Sandage, 1974), will be much
smaller than typical seeing discs at the required redshifts
$(z > 0.1)$.

There is another approach open to the ground based
astronomer and that is to choose a physical length _a priori_
and to project it out to the required redshifts according to
some cosmological model. This approach unfortunately does
not yield cosmologically model independent results. However,
the dependence on cosmological models is relatively small at
redshifts less than $z = 0.3$. This is the approach which we
have taken in this work.

The procedure is rather straightforward. We observed
the luminosity (L_{ob}) within an angular radius $\theta_{ob}(z)$. These
luminosities were determined with a fixed bandwidth and

and wavelength on the Earth and were corrected for K-dimming and galactic absorbtion. The details of these corrections can be found in Hoffman and Crane (1977 a). The quantity we wish to determine is the average surface brightness within a standard metric angular radius, $\theta_m(q, z)$. We have chosen a physical radius of 10.15 kpc and used the standard Friedmann cosmologies with $q_o = \frac{1}{2}$ (see Weinberg, 1972) and $H_o = 50$ Km s^{-1} Mpc^{-1} to determine $\theta_m(\frac{1}{2}, z)$ at the required redshifts. We must also correct L_{ob} for the fact the $\theta_{ob}(z)$ might not equal $\theta_m(q, z)$. Following Gunn and Oke (1975), we assume that the galaxian growth curve is a power law (with power $\alpha \cong 0.75$) and correct L_{ob} to $L_m = L_{ob}(\theta_m(\frac{1}{2},z)/\theta_{ob}(z)^{\alpha}$. We then determine

$$SB(q_o = \frac{1}{2}, z) = L_m / \pi \theta_m^2(\frac{1}{2}, z) \qquad (1)$$

If, in fact, $q_o = \frac{1}{2}$, then this surface brightness is the quantity to be tested for $(1+z)^{-4}$ dependence. To remove the q_o dependence, we rewrite Equation 1

$$SB(z) = \left\{ \frac{L_{ob}}{\pi \; \theta_{ob}^{\alpha}(z) \; \theta_m^{2-\alpha}(\frac{1}{2}, z)} \right\} \left[\frac{\theta_m(\frac{1}{2}, z)}{\theta_m(q, z)} \right]^{2-\alpha}$$

This is the cosmological model independent quantity which is to be used to test the $(1+z)^{-4}$ dependence of surface brightness. It should be noted that this expression contains exactly the same dependence on (or independence of) q_o as the conventional expression for the redshift-magnitude relation. (Gunn and Oke, 1975).

According to the conventional wisdom, one should include a chemical evolution term (Larson and Tinsley, 1974) and a dynamical evolution term (Ostriker and Tremaine, 1975) on the

534

right of Equation 2 if SB(z) is to maintain the $(1+z)^{-4}$
dependence. Since dynamical evolution is not well understood,
we will ignore it, and approximate the chemical evolution
correction by (see Tinsley, 1972)

$$EV(z) = (1+z)^{-0.33}$$

In order to illustrate the magnitude of these effects, we
rewrite Equation 2

$$SB(z) = SB_{ob}(z) \ Q(z)EV(z)$$

where $SB_{ob}(z)$ is the term in curly brackets in Equation 1,
and $Q(z) = \theta_m (z,\frac{1}{2})/\theta_m(z,q)^{2-\alpha}$. EV(z) and Q(z) for
$q_o = 1.0$ and 0.06 are plotted in Figure 1. The evolutionary
term is always 1/12th of the expansion and has the effect
of making the observed q_o larger than the true q_o. The
cosmological term Q is also on the order of 1/12 the expansion
for $0.06 < q_o < 1.0$. Of course, in practice q_o and evolution
are not well determined, and cannot be applied as corrections
to observation such as K-dimming is, but must be determined
from the data.

In our observations, the luminosity, L_{ob}, mentioned
above was, in fact, the "characteristic luminosity" L*
derived from a luminosity function of the type discussed
by Schechter (1976). The data were obtained from observations
by Hoffman and Crane (1977 a) and include luminosities for
1086 galaxies in six clusters with redshifts ranging from
z = 0.05 to z = 0.20. The procedures for obtaining the
characteristic luminosity from these observations are available
(Hoffman, 1975; Hoffman and Crane, 1977b). The table below
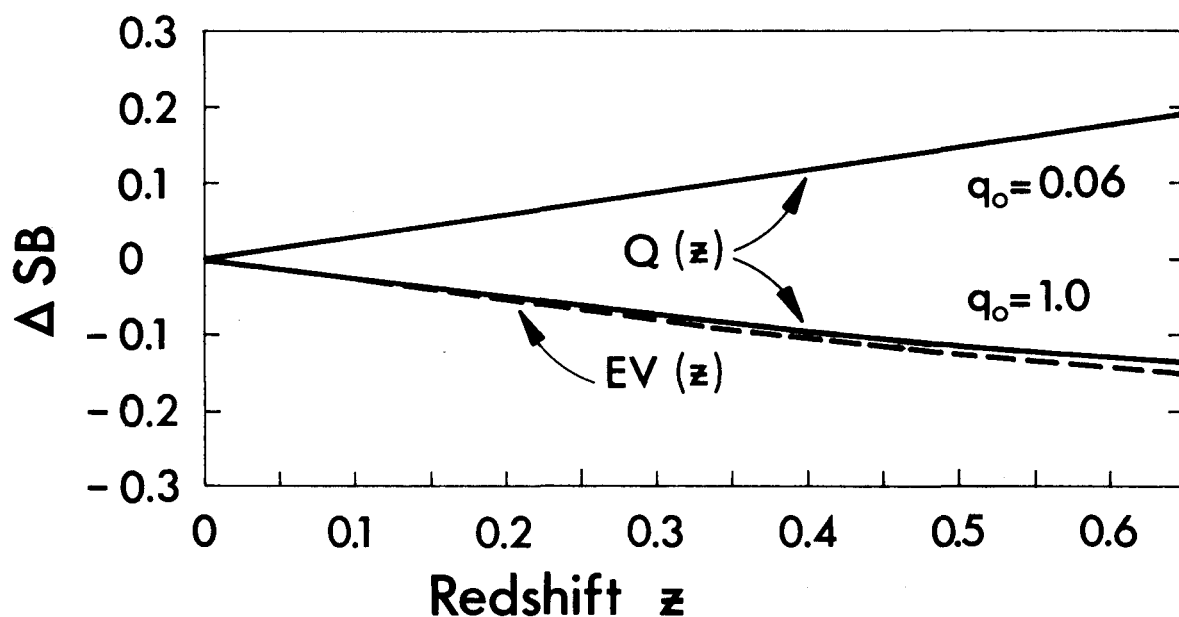list the data relevant to this discussion.

Figure 1: Corrections for evolution, EV(z), and for $q_o \neq \frac{1}{2}$ Q(z). These are corrections to be applied to the observations $SB_{ob}(z)$ to remove these two effects from the data. Q(z) is calculated with $\alpha = 0.75$.

Table 1: Cluster Surface Brightness Data

Abell (1)	Name (2)	z (3)	$m(SB_{ob})$ (4)	σ (5)
1377	Ursa Major 1	0.0516	22.20	0.21
2065	Corona Borealis	0.0722	22.55	0.15
1132	Ursa Major II	0.1345	22.83	0.16
1413	-	0.1426	22.58	0.11
801	-	0.1917	22.78	0.30
732	Hydra II	0.2018	23.20	0.27

Notes to Table 1: Column 1, Abell Cluster Number (Abell 1958); Column 2, Cluster name if any; Column 3, Redshift in units of v/c; Column 4, Characteristic surface brightness in V magnitudes/ $(arcsec)^2$, m(SB) = -2.5 log SB; Column 5, Uncertainty in $m(SB_{ob})$ same units.

536

This data set has several advantages over other
available data sets for the purpose of the surface bright-
ness test. All galaxies in all clusters have been treated
identically. Each L_{ob} contains information averaged over
more than a hundred galaxies per cluster and is therefore
quite independent of variations in individual galaxies. We
have used somewhat smaller apertures, θ_{ob}, than previous
observers and this tends to increase the value of α
mentioned above and, hence, reduce the sensitivity of our
results to our choice of cosmology. The individual galaxy
luminosities were individually corrected for seeing effects
so that inspite of our smaller apertures, we do not degrade
the results because of seeing. We have eliminated the
aperture correction by choosing $\theta_{ob}(z) \equiv \theta_{met}(z)$.

The data of Table 1 have been fit to a function of the
form m(SB) = 2.5 a log (1+z)+b. The results are a = 4.10$\pm$
1.62, b = 22.12$\pm$ 0.21 with a χ^2 of 4.53 for 4 degrees of
freedom. Figure 2 shows a plot of the data and the fitted
result. The conventional interpretation of redshifts
predicts a $\equiv$ 4 in the absence of evolution. Tired light
cosmologies (Geller and Peebles, 1972) or any other model
in which the redshift depends only on the light travel
distance (Pecker et al., 1973) predict a $\equiv$ 1. Our results
rule out models with a = 1 at the 94% confidence level.
However, this must be slightly qualified since tired light
cosmologies allow varied predictions for the metric radius
versus redshift relation (see Geller and Peebles 1972) and
in the absence of other compelling information, we have
chosen tired light metric radii which match our $q_o = \frac{1}{2}$ radii
at z < 0.2. This represents a tired light cosmology in a
closed curved space. For spaces with larger radii of
curvature, our result is not as strong.
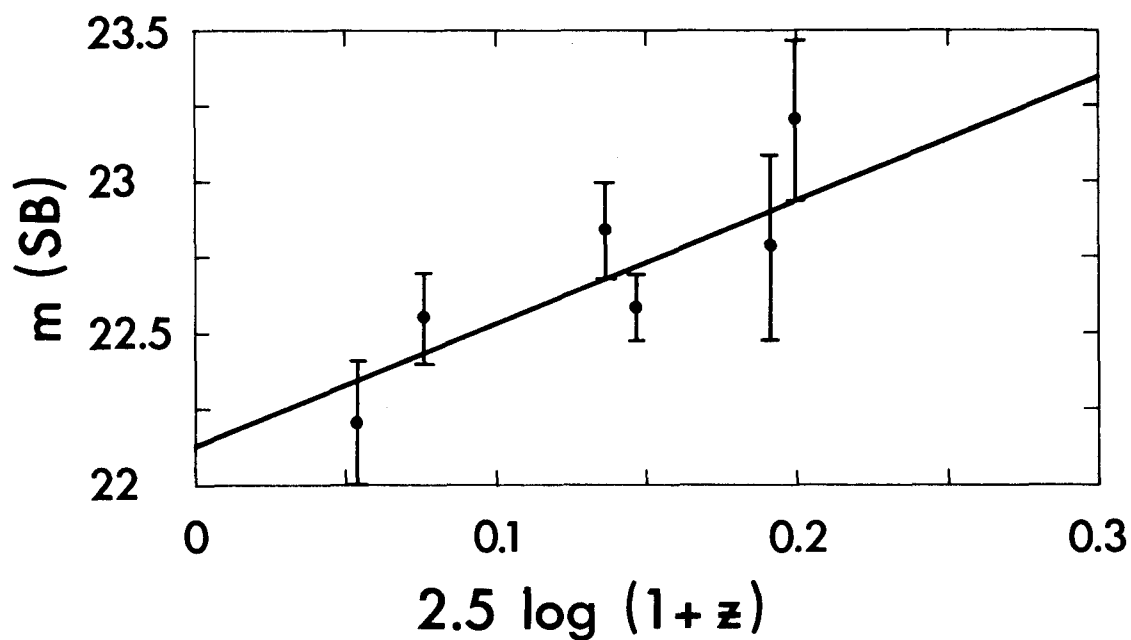
Figure 2: Plot of the observed surface brightness
SB(z) vs 2.5 log(1+z). The line has been
determined from the values given in the text
for our results. The units of surface brightness
are magnitudes per (arcsecond)^2.

In addition, we can show that the characteristic
luminosity, L*, is a good standard candle out to z = 0.20
having a dispersion $\sigma(m_v*)$ = 0.19 compared to $\sigma(M_1)$ = 0.51
for these same clusters. By design, the results contain
no information on the value of 90 or on evolution.

References

Crane, P., 1976, Ap.J. (Letters) ,206, L 133.

Geller, M.J. and Peebles P.J.E.,1972 Ap. J., 174, 1.

Gunn, J.E., and Oke, J.B. 1975 Ap.J., 195, 255.

Hoffman, A.W. 1975, PhD. Thesis, Princeton University
        (unpublished)

Hoffman, A.W., and Crane P. 1977a, Ap.J. (in press)

Hoffman, A.W.,and Crane P. 1977b, (in preparation)

Larson, R.B., and Tinsley B.M., 1974, Ap.J., 192, 293.

Misner, C.W., Thorne, K.S., and Wheeler, J.A. 1973,
        Gravitation (San Francisco: W.H. Freeman & Co) pp 584.

Ostriker, J.P., and Tremaine, S.D., 1975, Ap.J. (Letters),
        202, L 113.

Pecker, J.C., Tait, W., and Vigier, J.P. 1973, Nature, 241, 338.

Sandage, A.R. 1974, in Large Space Telescope, AIAA 12th
        Aero Sci. Meeting Washington D.C.

Schechter, P. 1976, Ap.J., 203, 297.

Tinsley, B.M., 1972, Ap.J. (Letters), 173, L 93.

Weinberg, S., 1972, Gravitation and Cosmology (New York:
        John Wiley and Sons).

DISCUSSION

K. RUDNICKI: How would your results be affected by the systematic obser-
vational errors connected with differences of angular diameters of gal-
axies with different z.

P. CRANE: We have chosen a specific cosmological model to determine the
metric angular diameters at different redshifts. If our cosmological
model is wrong, then we must modify the luminosity we measure by the
amounts shown in Figure 1. This will then affect the results accordingly,
but at redshifts less than 0.2 this will be quite small.

G. DE VAUCOULEURS: 1) Did you measure a nearby cluster, such as Virgo,
where the measurements could be compared with other data?
2) How many objects did you measure in each cluster and how were they
calibrated?

P. CRANE: 1) For two of the clusters we have comparisons with other
observers. These comparisons indicate that there are no systematic
errors in the magnitudes we have determined which would affect our re-
sults.
2) We measured a minimum of about 60 and a maximum of about 300 objects
in these clusters. The magnitude scales were determined by comparison
with several photoelectric magnitudes in each cluster. The dispersion
of our results around the photoelectric results is $\sigma \approx 0.05$ magnitudes.

V. PETROSIAN: The main difference between the tired-light and expanding
models - the two powers of $(1 + z)$ - come from the absence of abberation
in the tired-light model. This must be taken into account in the correc-
tion term $Q(z)$. Once this is done in the present analysis the expected
relation between surface brightness and redshift in the tired-light model
will be approximately $SB(z) \sim 1 + z)^{-3+\alpha}$, so that the tired-light model
can be ruled out only at one σ level. I would like to emphasize that the
insensitivity of the surface brightness test is basic (as described by
myself and B. Tinsley; cf. figure 1 of my paper on surface brightness)
and cannot be overcome by a different analysis. These comment apply
also to Spinrad's results.