H II galaxies as deep cosmological probes

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Abstract
We re-investigated the use of the Hubble diagram to measure the cosmological constant (Λ) and the mass density of the Universe (ΩM). We find an important focusing effect in Λ for redshifts of about 3. This effect implies that the apparent magnitude of a standard candle at redshifts z = 2–3 has almost no dependence on Λ for ΩM > 0.2. This means that ΩM can be measured independently of ΩΛ by targeting the redshift range according to an estimate of the value of ΩM.

We explore the evidence in support of the suggestion that extreme starburst galaxies, also known as H II galaxies, can be used as distance estimators over a wide range of redshifts and reaching very high values. We have compiled literature data of H II galaxies up to z ~ 3 and found a good correlation between their luminosity and velocity dispersion measured from their strong emission lines, thus confirming the correlation already known to exist for H II galaxies in the nearby Universe. Several systematic effects, such as age, extinction, kinematics and metallicity, are discussed, as well as the effects of different cosmologies.

Key words: H II regions – galaxies: fundamental parameters – galaxies: ISM – galaxies: irregular – cosmology: miscellaneous – distance scale.

1 Introduction
Recent results from distant supernova surveys have yielded values of ΩM (the matter density parameter of the Universe) so low (in fact negative for Λ = 0) that they seem unphysical and in disagreement with cosmic microwave background (CMB) results. This inconsistency has led to a renewed exploration of cosmological models with cosmological constant Λ (Lineweaver 1998; White 1998).

Non-zero Λ has been invoked before to solve inconsistencies or apparent discrepancies, such as the expansion age of the Universe versus the age of globular clusters, but the most compelling evidence for Λ ≠ 0 comes from the combination of the observed CMB anisotropy and the constraints from distance type Ia supernovae (SN) (see Efstathiou et al. 1999 for a recent review).

The use of supernovae to measure simultaneously ΩM and ΩΛ (the energy density of vacuum) was pioneered by Goobar & Perlmutter (1995) and nicely demonstrated by Perlmutter et al. (1998) and Riess et al. (1998), who showed that type Ia SN at redshifts 0.1 < z < 1 could strongly constrain the allowed range in these cosmological parameters. Unfortunately, the results of the two groups are still inconsistent at the 2σ level, although when combined they tend to favour models with low matter density (ΩM ≲ 0.4) and non-zero Λ (Efstathiou & Bond 1999; Efstathiou et al. 1999).

In this paper we show that the strong focusing effect of Hubble diagrams with cosmological constant allows one to separate cleanly the effects of mass density and vacuum density in the expansion, provided one can measure distances in the range 1 < z < 3. At z = 2–3, the discrimination between different values of ΩM reaches up to one magnitude in distance modulus, and is only very weakly dependent on ΩΛ, while knowing ΩM, the discrimination in ΩΛ is largest for z = 0.6–1 and reaches about 0.5 mag at z ~ 1 for ΩM = 0.2.

It is therefore desirable to explore distance estimators like the L(Hβ)–σ relation in H II galaxies (Melnick, Terlevich & Moles 1988, hereafter MTM) that can potentially be used from the local group of galaxies up to z ~ 4 with today’s technology. In this paper, we use published data to show that the L(Hβ)–σ relation for local galaxies is also satisfied by emission-line objects of redshifts up to z = 3. We argue that strong emission-line galaxies are very promising objects to be used for a global determination of the cosmological parameters ΩM and ΩΛ.

2 The redshift–magnitude diagram in Λ ≠ 0 cosmologies
The emission-line luminosity of an object is related to the
observed emission-line flux through the luminosity distance parameter $D_L$, which depends on the cosmological parameters $\Omega_M$ and $\Omega_\Lambda = \Lambda/(3H_0^2)$ as (Refsdal, Stabell & de Lange 1967)

$$D_L = \frac{c(1+z)}{H_0\sqrt{\Omega_M}} f[\Omega_M^{1/2} I(z, \Omega_M, \Omega_\Lambda)],$$

$$I(z, \Omega_M, \Omega_\Lambda) = \int_0^1 [(1+z')^2(1 + \Omega_Mz') - z'(2+z')\Omega_\Lambda]^{-1/2} dz',$$

where

$$F[x] = \sin(x) \text{ for } \Omega_M + \Omega_\Lambda > 1,$$

$$\sinh(x) \text{ for } \Omega_M + \Omega_\Lambda < 1,$$

and $\Omega_\Lambda = 1 - \Omega_M - \Omega_\Lambda$ in both cases. $F[x] = x$ and $\Omega_\Lambda = 1$ for $\Omega_M + \Omega_\Lambda = 1$.

For $D_L$ in Mpc, the relation between apparent ($m$) and absolute ($M$) emission-line or continuum magnitudes is given by $m = M + 5 \log D_L + 25$.

An important and perhaps surprising feature of the Hubble diagrams with non-zero cosmological constant is the strong focusing or convergence effect mentioned byRefsdal et al. (1967). This is shown in Fig. 1, which plots the predicted luminosity distance (normalized to $\Omega_M = 0.5$ and $\Omega_\Lambda = 0$) as a function of redshift for different combinations of cosmological parameters. For a given $\Omega_M$, the world models of different $\Omega_\Lambda$ converge in a narrow redshift range and the degree of convergence increases with increasing mass density. The redshift at which the convergence occurs diminishes with increasing values of $\Omega_M$. In particular, for $\Omega_M = 0.5$ the convergence redshift is about 2.8; for $\Omega_M = 1.0$ it is about 2.3 and for $\Omega_M = 2.0$ about 1.7. For $\Omega_M = 0$ (not shown in the figure) there is no convergence, while for $\Omega_M < 0.2$ the critical redshift is $z \approx 10$.

As discussed in the Introduction, this effect allows the accurate determination of $\Omega_M$ independently of the value of $\Omega_\Lambda$. For small $\Omega_\Lambda$, the optimum redshift range is $z \sim 3$ where a large sample of H II galaxies already exists. The existence of this focusing also implies that the best range to determine $\Omega_\Lambda$ using the magnitude-redshift method is either $z < 1$ or $z > 5$.

### Figure 1
Normalized distance modulus $\Delta(m - M) = (m - M)_{0,0,\Omega_0} - (m - M)_{0,0,1.0}$ as a function of redshift. For each value of $\Omega_M$ as labelled in the figure, we plot a family of vacuum energy density $\Omega_\Lambda = 0, 0.25, 0.5, 0.75$ and 1.0. For each family, the dashed line corresponds to $\Omega_\Lambda = 1$.

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3 THE DISTANCE ESTIMATORS WITH WIDE REDSHIFT RANGE

The classical empirical distance estimators for spiral and elliptical galaxies (Tully–Fisher and $D_n$–$\sigma$) cannot be applied to galaxies at large redshifts (say $z > 0.5$) because of significant systematic evolution of the stellar populations with look-back time (Schade, Barrientos & López-Cruz 1997; Rix et al. 1997; Vogt et al. 1997; Van Dokkum et al. 1998). Thus, even if we could measure the relevant parameters with the next generation of ground-based and space telescopes, it is still unclear whether it will be possible to use these techniques to determine reliable distances of galaxies at $z > 0.5$.

Type Ia SN are good standard candles (see e.g. Perlmutter et al. 1998; Riess et al. 1998, and references therein) with errors less than 0.4 mag for a single SN up to redshifts of about 0.8. There are, however, discrepancies between the results of Perlmutter et al. and Riess et al., which may be related to uncertainties in the extinction corrections or other as yet unknown systematic effects such as metallicity. Nevertheless, SNIa still provide the most accurate method that can be used up to $z \sim 1$ with present-day instrumentation.

A potentially very powerful technique that has received relatively little attention in the literature is the $L(H\beta)$–$\sigma$ relation for H II galaxies. The correlation between the $H\beta$ luminosity [$L(H\beta)$] and the velocity width of the lines ($\sigma$) described by Terlevich & Melnick (1981) was calibrated as a distance indicator for a sample of nearby galaxies ($z < 0.1$) by Melnick et al. (1987, see also MTM) using giant H II regions in nearby late-type galaxies to fix the zero-point. As the (bolometric) luminosities of H II galaxies are dominated by one or more starburst components, their luminosities per unit mass are very large. In spite of being low-mass objects, H II galaxies can therefore be observed out to redshifts of cosmological interest.

By selecting star-forming galaxies with the strongest emission line (i.e. with the largest equivalent widths), one effectively selects the youngest objects within a narrow age range (Copetti, Pastoriza & Dottori 1986). This selection criterion guarantees that, at least to first order, the $L(H\beta)$–$\sigma$ distance estimator is free from the evolution effects in the stellar population that bedevil the traditional techniques. Moreover, the extinction and the metallicity of these galaxies can be directly determined from their emission-line spectra. Even possible systematic changes in metallicity with redshift, for example, can therefore be included in a relatively straightforward way, because oxygen abundances can be directly determined with the new generation of IR spectrographs on 8-m class telescopes. Although H II galaxies are to first order free from the systematic effects that plague SNIa, the error in the distance modulus for a given galaxy in the current calibration is about twice that of SNIa. However, most of the scatter in the correlation is caused by observational errors, which can be substantially reduced using modern instruments and detectors.

The $L(H\beta)$–$\sigma$ relation has recently been verified to hold also for star-forming faint blue galaxies at redshifts of about $z \sim 0.5$ (Koo et al. 1996), which constitutes a first very important step towards its use as a deep cosmological probe.

4 THE H II GALAXIES DATA SET

The sample used by MTM to calibrate the distance indicator is limited to $z < 0.1$. In order to extend this sample to distances of
cosmological interest, we have searched the literature for galaxies at $z > 0.1$ having very strong and narrow emission lines. Unfortunately, such objects are rare in catalogues of faint blue galaxies at intermediate redshifts, but many objects with moderate emission-line strengths have been found in deep photometric searches. Koo et al. (1994, 1995) and Guzmán et al. (1996, 1998) have published images and high-resolution spectra of 17 faint ($B = 20–23$) blue galaxies with narrow lines at redshifts between 0.1 and 1. Their images, spectra, luminosities, and line widths are a close match to those of the nearby H II galaxies, so Koo and collaborators concluded that H II galaxies are the local counterparts of their intermediate-redshift compact blue galaxies.

Guzmán et al. (1997) published data for 51 compact galaxies in the Hubble Deep Field (HDF), of which 27 are classified as ‘H II-like’. They (and also Koo et al.) give emission-line widths ($\sigma$), absolute blue magnitudes ($M_B$) and H$\beta$ equivalent widths [W(H$\beta$)] obtained with the Keck I telescope. The authors also give H$\beta$ luminosities, which they derive from the absolute blue magnitudes and equivalent widths following Terlevich & Melnick (1981).

A few Lyman-break galaxies show strong emission lines. Pettini et al. (1998) have presented near-IR spectroscopy of five Lyman break galaxies at $z \sim 3$. Two of these galaxies have luminosities and velocity dispersions typical of H II galaxies. A third one has very strong lines [W(H$\beta$) > 50 Å], but the velocity dispersion ($\sigma = 190$ km s$^{-1}$) is too large for H II galaxies (see below). No H$\beta$ fluxes or equivalent widths are available for the remaining two objects.

Fig. 2 shows the $L(H\beta) - \sigma$ relation for the galaxies in the samples above as follows. Filled triangles represent the data for local galaxies from MTM. Squares show the data from Koo et al. (1995) and Guzmán et al. (1997). Circles represent the high-redshift objects from Pettini et al. (1998). The solid line shows the MTM fit to the local objects. Because no extinction measurements are available for the intermediate- and high-redshift samples, the local sample galaxies are plotted in Fig. 2 without extinction corrections.

**Figure 2.** The luminosity-$\sigma$ correlation for H II galaxies at a wide range of redshifts. The solid line shows the maximum-likelihood fit to the young H II galaxies in the local Universe. The dashed line shows the predicted $L(H\beta) - \sigma$ relation for an evolved population of H II galaxies. The cosmology is $H_0 = 65$, $q_0 = 0$, $\Lambda = 0$ in this figure.

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5 THE $L(H\beta) - \sigma$ RELATION AS A DISTANCE INDICATOR

The most important systematic effects in the $L(H\beta) - \sigma$ relation that need to be considered in order to apply the correlation to high-redshift galaxies are summarized below.

5.1 The physics of the $L(H\beta) - \sigma$ relation

There has been considerable debate in the literature concerning the interpretation of the emission-line profile widths in giant H II regions (GHR), which in many respects resemble H II galaxies and which, in particular, exhibit a similar correlation between $L(H\beta)$ and $\sigma$. In GHR, the coupling between the turbulence of the ionized gas ($\sigma$) and the total mass of the system (stars + gas) is very complex and appears to evolve with time. For young GHR, $\sigma$ is therefore coupled to gravity through the stirring motions of low-mass stars, while for evolved objects this coupling is lost and the gas motions are dominated by stellar winds from massive stars (see Melnick, Tenorio-Tagle & Terlevich 1999 for a recent review). It is still not known whether age is the only (or the dominant) parameter, or whether environment also plays an important role, but the fact that GHR with a wide range of ages fit the $L(H\beta) - \sigma$ relation suggests that the total mass of the objects is what determines $\sigma$.

The situation for H II galaxies is different. Telles (1995) showed that these objects define a fundamental plane that is remarkably similar to that defined by normal elliptical galaxies (Fig. 3). This result lends strong support to the interpretation of Terlevich & Melnick (1981) and MTM that the emission-line profile widths of giant H II galaxies directly measure the total mass of these systems within the measuring radius. Therefore, besides systematic effects, which are discussed below, the scatter in the $L(H\beta) - \sigma$ relation suggests that Telles used continuum magnitudes and not $L(H\beta)$ depends among other things on the existence of a second parameter (see below), on possible variations of the initial mass function (IMF), on the importance of sources of broadening not related to a young stellar component (e.g. rotation), and on the duration of the burst of star formation that powers the emission lines.

MTM showed that this scatter can be reduced by restricting the sample to objects with $\sigma < 65$ km s$^{-1}$. The same result was found by Koo et al. (1995) for intermediate-redshift objects. This cut-off can be understood if one assumes that H II galaxies are powered by clusters of coeval stars (starbursts). The cut-off results from imposing the condition that the time required for the clusters to form (e.g. the free-fall time) must be smaller than the main-sequence lifetime of the most massive stars. One of the two galaxies at $z = 3$ plotted in Fig. 2 appears to exceed this limit, but the measurement error ($\pm 20$ km s$^{-1}$) is still rather large.

5.2 Age effects

In order to minimize systematic effects caused by the rapid evolution of the ionizing stars, MTM restricted their sample to galaxies with $W(H\beta) > 25$ Å. In fact, this restriction has a double purpose, which is particularly relevant for high-$z$ objects: it selects the young(est) starbursts, and eliminates objects with significant underlying old(er) stellar populations. The latter is critical because an old stellar population may widen the emission lines in a way that is uncorrelated with the luminosity of the young component.
There are only a few objects in our intermediate-redshift sample with \( W_{\text{H} \beta} \). These are plotted with filled symbols in Fig. 2. The open symbols show the data for objects with weaker lines. As expected, these objects do not fit the correlation defined by the local H\( \text{II} \) galaxies, which have a mean line strength of \( k_{W_{\text{H} \beta}} \approx 10^5 \) Å.

The luminosity evolution of a young coeval starburst during the first \( 10^7 \) yr proceeds as a rapid decay of the emission-line flux after the first 3 Myr at roughly constant continuum flux until about 6 Myr. Thus, in this range of ages the age-dimming in \( L(\text{H} \beta) \) can be directly estimated from the change in equivalent widths (Terlevich & Melnick 1981; Copetti et al. 1986). The mean equivalent width of the objects plotted as open squares in Fig. 2 is \( \langle W(\text{H} \beta) \rangle = 11 \) Å, so evolution reduces the average H\( \beta \) luminosity of the sample by a factor 105/11. The dashed line shows the MTM relation affected by this amount of evolution. The fit is seen to be more than acceptable, confirming our conclusion that most objects are evolved starbursts rather than strong starbursts on top of a bright, older stellar population.

Note, however, that two of the weak-lined galaxies fit the correlation without luminosity corrections. These objects have high H\( \beta \) luminosities but also very strong continua, indicating the presence of a significant underlying older stellar population. The Hubble Space Telescope (HST) images of one of these galaxies (H1-3618) by Koo et al. (1994) show that this object is very compact, indicating that the strong continuum does not come from a bright underlying galaxy, but is most likely the light from a previous starburst.

Another indication that the objects in the intermediate-redshift sample are in general more evolved than the local sample ones comes from the excitation of the nebular gas as measured by the ratio of \( [\text{O} \text{III}] / \text{H} \beta \). The mean value from Guzmán et al. (1997) is \( \langle [\text{O} \text{III}] / \text{H} \beta \rangle = 2.2 \pm 0.5 \) while the mean for the MTM sample is \( \langle [\text{O} \text{III}] / \text{H} \beta \rangle = 5 \pm 2 \), where the quoted errors are the (1σ) widths of the distributions.

### 5.3 Extinction effects

Extinction corrections for local H\( \text{II} \) galaxies are determined in a straightforward manner from the Balmer decrements (MTM). Fig. 4 presents a histogram of the extinction for the MTM galaxies.
at high galactic latitudes \((b > 30^\circ)\) in order to minimize the contribution of foreground galactic extinction. The extinction is strongly peaked at a value of \(A_{H\beta} = 0.8\) mag, with a mean value of \(A_{H\beta} = 1.1\) mag and an rms value of 0.5 mag. Restricting the sample to the luminosity range covered by intermediate-redshift objects \([\log(L(H\beta)) > 41.0]\) gives a slightly larger value \(A_{H\beta} = 1.25\) mag with similar dispersion.

It is rather difficult to measure the Balmer decrement for low signal-to-noise ratio (S/N) observations of intermediate- and high-redshift H\,\textsc{ii} galaxies and it is normally not done, so no extinction values are available for the intermediate- and high-redshift galaxies in our sample. Future observations with 8-m class telescopes should ideally include H\,\beta and H\,\gamma to permit direct estimates of the reddening in high-\(z\) H\,\textsc{ii} galaxies.

### 5.4 Metallicity effects

In their calibration of the \(L(H\beta)-\sigma\) relation as a distance indicator, MTM found an important systematic shift in luminosity between the giant H\,\textsc{ii} regions in nearby late-type galaxies, used to determine the zero-point, and H\,\textsc{ii} galaxies, because of differences in the mean metallicities of the two samples.

The distribution of metallicities for the MTM H\,\textsc{ii} galaxies in our sample is presented in Fig. 5. The mean metallicity of the sample is \(12 + \log(O/H) = 8.02 \pm 0.18(\sigma)\), while if we restrict the sample to the most luminous objects, as described above, the mean metallicity is \(12 + \log(O/H) = 8.07 \pm 0.19(\sigma)\). Unfortunately, there are no metallicities available yet for the intermediate- and high-redshift objects in our sample, but clearly, in order to use the \(L(H\beta)-\sigma\) relation as a distance indicator, either the metallicities of the local and high-\(z\) samples must be similar or the luminosities must be corrected using O/H as prescribed by MTM.

In a pilot project to measure accurate metallicities and electron temperatures of H\,\textsc{ii} galaxies at redshifts between 0.2 and 1 (Terlevich et al., in preparation) we observed a sample of 20 low-metallicity candidates with the 3.6-m and NTT telescopes at La Silla. We could clearly detect the electron temperature sensitive faint line [O\,\textsc{iii}]\,\lambda\,4363\,\AA\ in the spectra of the five objects with the largest \(W(H\beta)\). A preliminary analysis of the data yields a mean oxygen abundance of \((12 + \log(O/H)) = 7.8\), significantly lower, in fact, than the mean value for the local sample. Recently, Kobulnicky & Zaritsky (1999, hereafter KZ99) have presented data for H\,\textsc{ii} G-like objects with redshifts \(0.1 < z < 0.3\). Their mean abundance, \((12 + \log(O/H)) = 8.4\), is significantly larger than the one we obtain for our NTT sample. However, KZ99 detect [O\,\textsc{iii}]\,\lambda\,4363\,\AA~(and hence measure electron temperatures) in only two of their objects, but for one of them the detection is marginal. The abundances of the other objects, estimated using the empirical \(R_{23}\) method, cannot be used with any confidence because the zero-point offset can be as large as 0.5 dex.

The abundance of the only object with a good measurement of electron temperature is \((12 + \log(O/H)) = 7.84\). Although KZ99 conclude tentatively that O/H in their intermediate-redshift sample is larger that in the nearby H\,\textsc{ii} galaxies, we think that direct measurements of electron temperatures are needed to support such a claim. Empirical methods are based on the underlying assumption that the ionizing properties of the young stellar populations are the same in the different objects, an assumption that must be checked when comparing objects over a wide range in redshifts.

We conclude that there is tentative, albeit contradictory, evidence that the abundances of higher redshift objects could be different from those of local H\,\textsc{ii} galaxies. Although the data are still very sparse and inaccurate, if real such an effect would introduce an important systematic bias in the estimation of distances to high-redshift objects that must be taken into account.

### 6 H\,\textsc{ii} Galaxies as Cosmological Probes

In order to illustrate the potential of H\,\textsc{ii} galaxies as deep cosmological probes, we have calculated the predicted distance moduli for the objects plotted in Fig. 2 using the most recent data from the literature (distances and oxygen abundances) for the giant H\,\textsc{ii} regions in order to recalculate the zero-point. The new calibration of the unbiased distance indicator introduced by MTM, \(M_Z = \sigma^2/(O/H)\), is thus given by

\[
\log[L(H\beta)] = \log(M_Z) + 29.5.
\]

![Figure 5. Distribution of oxygen abundances for H\,\textsc{ii} galaxies in the local Universe \((z < 0.1)\).](https://example.com/fig5)

![Figure 6. The differential Hubble diagram for H\,\textsc{ii} galaxies with a wide range of redshifts. The family of curves from Fig. 1 is also shown. The large symbols represent the average redshift and distance modulus for each subsample. The error bars show the mean error in distance modulus assuming that each data point is an independent measurement and ignoring observational errors. \(H_0 = 80\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}\) was used to normalize the data points. The model lines are independent of \(H_0\).](https://example.com/fig6)
from which the distance modulus is obtained as

\[(m - M) = 2.5 \log \frac{\sigma^2}{F(\text{H} \beta)} - 2.5 \log(O/H) - A_{\text{H} \beta} - 26.44, \]  

(1)

where \(F(\text{H} \beta)\) is the observed \(\text{H} \beta\) flux and \(A_{\text{H} \beta}\) is the total extinction.

Fig. 6 presents the resulting Hubble diagram for \(\text{H} \text{II}\) galaxies. The lines show the \(\Omega_M = 0.5\) family of models from Fig. 1. We have used constant values of \(A(\text{H} \beta) = 1.25\) and \(\log(O/H) = -3.9\) for all galaxies at \(z > 0.1\) to compute their distance moduli. These values correspond to the mean values of the objects in our local sample that span ranges in \(L(\text{H} \beta)\) and \(\sigma\) covered by our intermediate-redshift sample and which are closest to those of the \(z \sim 3\) galaxies (cf. Section 5). The large symbols show the average values for each subsample. The error bars show the mean error in distance modulus. Although our data set cannot be used (nor is intended) to place significant constraints on the cosmological parameters, it is very helpful to understand the limitations of the method.

Probably the first thing one notices is the large scatter in the data. The rms dispersion in distance modulus for the local sample is \(\sigma_{\Delta(m - M)} = 0.52\) mag. According to MTM, typical errors for these galaxies are 5 per cent in velocity dispersion and 10 per cent in flux. Adding errors of about 10 per cent in extinction and about 20 per cent in abundance, the expected scatter caused purely by observational errors is 0.35 mag in distance modulus. Thus, there seems to be room for improvement and errors similar to those for SNIa may be achievable with better quality data.

The second point is that the two high-redshift galaxies have distance moduli that are discrepant by more than one magnitude. While the observational errors are indeed large, this could also be caused by our choice of extinction and metallicity. These parameters enter with the same sign in equation (1), so systematic changes of 0.2 dex in O/H and 0.2 mag in extinction (which correspond to 1σ deviations in the local sample) translate into shifts of 0.7 mag in distance modulus. Notice that, because the maximum separation between \(\Omega_M = 0.2\) and \(\Omega_M = 1\) at \(z = 3\) is about 1 mag (Fig. 6), it is crucial to have good measurements of extinction and abundance for these objects.

Finally, we notice that, even with our new zero-point calibration, the data for local \(\text{H} \text{II}\) galaxies are inconsistent with the value of \(H_0 = 65\) km s\(^{-1}\) Mpc\(^{-1}\) that results from SNIa. We believe that the discrepancy arises from systematic errors in the photometry of giant \(\text{H} \text{II}\) regions, which we are in the process of checking using narrow-band CCD imaging. Clearly, however, provided there are no systematic differences in the photometric calibrations between local and distant objects, the determination of \(\Omega\) is independent of \(H_0\).

We believe that, using the new optical and IR spectrographs that are coming on-line on 8-m class telescopes, it will be possible to measure \(F(\text{H} \beta)\) to 10 per cent and \(\sigma\) to better than 5 per cent at \(z = 3\). An accurate determination of \(\Omega_M\), with rms error of about 0.05, therefore seems possible with samples of 40–50 \(\text{H} \text{II}\) galaxies at \(z = 1–3\). The determination of extinction and metallicity at this redshift, however, will remain a challenging observational problem.

7 CONCLUSIONS

Our exploration of the use of the magnitude–redshift method to determine the cosmological constant (\(\Omega_\Lambda\)) and the mass density of the Universe (\(\Omega_M\)) using \(\text{H} \text{II}\) galaxies led us to re-discover the important focusing effect in \(\Lambda\) for redshifts about 3. This effect implies that the apparent magnitude of a standard candle at redshifts \(z = 2–3\) has almost no dependence on \(\Omega_\Lambda\) for \(\Omega_M > 0.2\).

Our strong conclusion is that, using the redshift–magnitude diagram method, \(\Omega_M\) can be measured independently of the value of \(\Omega_\Lambda\) by targeting the redshift range according to an estimate of the value of \(\Omega_M\). In particular, for small \(\Omega_M\), the optimum redshift is \(z \sim 3\), where a significant sample of \(\text{H} \text{II}\) galaxies already exists (e.g. Pettini et al. 1998; Steidel et al. 1998).

We also find that the best range to determine \(\Omega_\Lambda\) using the redshift–magnitude method is well away from the redshift region where the focusing occurs, i.e. either \(z < 1\) or \(z > 5\).

Considering that we have very little control over the systematic effects discussed above for galaxies at \(z > 0.1\), we find it quite remarkable that the \(L(\text{H} \beta) – \sigma\) relation established by MTM for local \(\text{H} \text{II}\) galaxies is so well satisfied by objects with a wide range of redshifts extending up to \(z = 3\). Furthermore, the intermediate-redshift sample itself shows a \(L(\text{H} \beta) – \sigma\) correlation similar to that found in the local Universe. Therefore, we are confident that \(\text{H} \text{II}\) galaxies can potentially be used as cosmological probes out to redshifts \(z = 3–4\).

One should bear in mind that none of the intermediate- and high-redshift \(\text{H} \text{II}\) galaxies found thus far has very strong emission lines. For most objects this may be an effect of evolution plus the fact that we have not yet found the youngest galaxies at high redshifts. This is not surprising, because all the intermediate- and high-redshift objects we have used in this paper have been discovered using broad-band photometric techniques that miss objects with very weak continua. Searches are under way using narrow-band techniques that are revealing objects with redshifts \(z > 3\) and strong Lyman α lines (Huw, Cowie & McMahon 1998). We think that many of these may in fact be young \(\text{H} \text{II}\) galaxies. Using the high-efficiency IR spectrographs that are becoming available in the new generation of 8–10 m telescopes, it will be possible to determine the \(\text{H} \beta\) line widths, luminosities, and equivalent widths of these objects over a wide range of luminosities with high accuracy. This will allow, for the first time, the use of the distance estimator to probe the cosmological parameters out to unprecedented distances.

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