AGE DATING OF A HIGH-REDSHIFT QSO B1422+231 AT \( z = 3.62 \) 
AND ITS COSMOLOGICAL IMPLICATIONS

YUZURU YOSHII,¹,² TAKUI TSHIMOTO,³ AND KIMIAKI KAWARA⁴

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ABSTRACT

The observed Fe II (UV + optical)/Mg II \( \lambda \lambda 2796, 2804 \) flux ratio from a gravitationally lensed quasar B1422+231 at \( z = 3.62 \) is interpreted in terms of detailed modeling of photoionization and chemical enrichment in the broad-line region (BLR) of the host galaxy. The delayed iron enrichment by Type Ia supernovae is used as a cosmic clock. Our standard model, which matches the Fe II/Mg II ratio, requires the age of 1.5 Gyr for B1422+231 with a lower bound of 1.3 Gyr, which exceeds the expansion age of the Einstein–de Sitter \( \Omega_0 = 1 \) universe at a redshift of 3.62 for any value of the Hubble constant in the currently accepted range, \( H_0 = 60–80 \) km s\(^{-1}\) Mpc\(^{-1}\). This problem of an age discrepancy at \( z = 3.62 \) can be unraveled in a low-density \( \Omega_0 \lesssim 0.2 \) universe, either with or without a cosmological constant, depending on the allowable redshift range of galaxy formation. However, whether the cosmological constant is a required option in modern cosmology awaits a thorough understanding of line transfer processes in the BLRs.

Subject headings: cosmology: theory — galaxies: evolution — quasars: emission lines — quasars: individual (B1422+231)

1. INTRODUCTION

Ages of distant objects at high redshift, \( z > 1 \), unambiguously constrain the expansion age of the universe at that redshift and can be used to determine the ultimate fate of the universe (Turner 1991; Kennicutt 1996). There is a growing interest in use of Type Ia and II supernovae (SNe Ia and II) as a nucleosynthesis clock in interpreting the abundance pattern of heavy elements seen in the spectra of high-redshift galaxies (Hamman & Ferland 1993; Matteucci & Padovani 1993).

Extensive calculations of explosive nucleosynthesis show that SNe II are the sites of alpha and iron production, whereas SNe Ia produce a large amount of iron relative to alpha elements (Nomoto, Thielemann, & Wheeler 1984). Since progenitors of SNe Ia have a lifetime of \( t_{\text{Ia}} \sim 1 \) Gyr, which is longer by 2 or 3 orders of magnitude than SNe II (Truran 1987), the switchover of the iron source from SNe II to SNe Ia creates a break in the alpha/iron abundance ratio at a time at which a significant number of SNe Ia start to explode. Accordingly, the nucleosynthesis clock records such a switchover and assigns an age above or below \( t_{\text{Ia}} \) 1 Gyr depending on whether the alpha/iron ratio is smaller than or equal to that of SN II origin, respectively. This feature acts like an alarm clock set at \( t_{\text{Ia}} \sim 1 \) Gyr and motivates us to measure the alpha/iron ratio at \( z \geq 3 \) in order to obtain a firm constraint on the expansion age of the universe to be compared with that derived from the Hubble constant, for which we adopt \( H_0 = 60–80 \) km s\(^{-1}\) Mpc\(^{-1}\) (Freedman 1998) as the current best estimate.

Among various alpha elements, magnesium is ideal for comparing with iron, because the best-studied range of rest-frame wavelengths from 1500 to 6000 Å includes the emission features of Fe II multiplet lines and Mg II \( \lambda \lambda 2796, 2804 \) doublet lines, so the ratio of their fluxes, which are emergent from the same ionized zone, is a direct indicator of the abundance ratio (Wills, Netzer, & Wills 1985). These wavelengths are redshifted to the near infrared at \( z \geq 3 \), and quasars are the only objects that are bright enough for their spectra to be studied. In this regard, Kawara et al.’s (1996) infrared observation of the Fe II to Mg II flux ratio for the gravitationally lensed quasar B1422+231 at \( z = 3.62 \) is particularly important. In this Letter, we compare their data with detailed models of chemical enrichment and attempt to determine the age of the broad-line region (BLR) in B1422+231, which allows us to set a combined constraint on the cosmological parameters and the epoch of galaxy formation.

2. BASIC EQUATIONS FOR CHEMICAL EVOLUTION

The strength of Fe II emission from quasars at various redshifts implies a much more significant iron supply from SNe Ia to the gas in the BLR of quasars as compared with the solar neighborhood (Wills et al. 1985; Elston, Thompson, & Hill 1994; Kawara et al. 1996). Such an iron-rich gas results if quasar host galaxies are associated with an initial burst of star formation and then the ejected iron from SNe Ia is restored to the gas after the burst and the cessation of star formation. This situation is explored by modeling the chemical enrichment with two basic ingredients (Tinsley 1980), such as (1) the star formation rate (SFR) proportional to some power of the gas fraction \( C(t) = n_t(t) \) and (2) the initial stellar mass function (IMF) having a time-invariant mass spectrum \( \phi(m) dm \propto m^{-\alpha} \) normalized to unity between the lower and upper mass limits \( (m_l, m_u) \).

The SFR coefficient for quasar host galaxies has been constrained in a narrow range from a variety of their observed features, that is, \( n_{\text{SFR}} = 7.5 \) Gyr\(^{-1}\) from their metal abundances (Padovani & Matteucci 1993; Matteucci & Padovani 1993) and \( n_{\text{SFR}} = 6.7–7.6 \) Gyr\(^{-1}\) from the N IV and N v/He II line ratios of high-redshift quasars (Hamann & Ferland 1992, 1993) having high metallicities like B1422+231. We therefore adopt the higher value of \( n_{\text{SFR}} = 7.6 \) Gyr\(^{-1}\) as the standard value in this paper. Theoretical arguments indicate that the IMF originates from fragmentation of the gas cloud that occurs almost independently of local physics in the gas (Low & Lynden-Bell 1976; Silk 1977). A solar neighborhood IMF would therefore be a good approximation, and we adopt a Salpeter slope of...
x = 1.35 and a mass range from \( m_1 = 0.05 \) to \( m_2 = 50 \ M_\odot \) (Tsujimoto et al. 1997). Then the gas fraction \( f_\text{g}(t) \) and the heavy-element abundance \( Z(t) \) in the gas change with time according to

\[
\frac{df_\text{g}}{dt} = -C(t) + \int_{m_\text{max}(m_\text{m}, m_\text{s})}^{m_\text{m}} d\phi(m) r(m) C(t - t_\text{m}),
\]

\[
\frac{dZ(t)}{dt} = -Z(t) C(t) + \int_{m_\text{max}(m_\text{m}, m_\text{s})}^{m_\text{m}} d\phi(m) \gamma_\text{m} \int_0^{t_\text{m}} dt_\text{m} g(t_\text{m}) C(t - t_\text{m})
\]

\[
+ \int_{m_\text{max}(m_\text{m}, m_\text{s})}^{m_\text{m}} d\phi m_\text{m} (1 - A) \phi(m) [Z(t) - Z(t - t_\text{m})] r_\text{m}(m) C(t - t_\text{m}),
\]

respectively, where \( m_\text{m} \) is the turnover mass when the main-sequence lifetime, \( t_\text{m} \), is equal to time \( t \), \( r(m) \) is the fraction of the ejected material from a star of mass \( m \), \( r_\text{m}(m) \) is the fraction of the ejected material without newly synthesized elements from that star, and \( \gamma_\text{m} \) is the heavy-element yield from an SN II or Ia. Since all these stellar quantities, either calibrated or constrained by nearby stars, should also apply to any galaxy, we can use the formula of Renzini & Buzzoni (1986) for \( m_\text{m} \) and the updated nucleosynthesis calculations by Nomoto’s group (Tsujimoto et al. 1995) for high-redshift galaxies.

The fraction of stars that eventually produce SNe Ia is

\( A = 0.055 \) for 3–8 \( M_\odot \) and \( A = 0 \) outside this mass range. The lifetime of their progenitors is \( t_\text{m} \approx 1.5 \) Gyr and its possible spread is modeled using the power-law distribution function \( g(t_\text{m}) \propto t_\text{m}^{-\gamma} (\gamma \geq 0) \) that is bounded in a specified range of \( t_\text{m} \) and normalized to unity. These basic quantities \( A \) and \( t_\text{m} \) for SNe Ia have been constrained mainly from the observed [O/Fe] break at [Fe/H] \(-1\) in the solar neighborhood (Yoshii, Tsujimoto, & Nomoto 1996). From theoretical considerations, Kobayashi et al. (1998) recently proposed that SNe Ia should occur only when the progenitor’s metallicity is above a critical value of [Fe/H] \(-1\). While this implies that the [O/Fe] break at [Fe/H] \(-1\) may only weakly constrain \( t_\text{m} \), the introduction of a critical metallicity for SNe Ia resolves an observational puzzle (Carney 1996): the Galactic globular clusters (GCs), spanning an age difference of several Gyr, exhibit a constant alpha/iron abundance ratio of the SN II origin all the way from [Fe/H] \(-2\) to \(-0.5\) without a break. In fact, with this critical metallicity, the GC data place even firmer limits of \( t_\text{m} = 1–3 \) Gyr from the box-shaped g-distribution with \( \gamma = 0 \) (Tsujimoto & Yoshii 1998). We therefore use this constraint on \( t_\text{m} \) to date the delayed enrichment of iron relative to alpha elements in high-redshift galaxies.

3. AGE DATING FOR THE B1422+231 SYSTEM

The rest-frame UV–optical spectrum of B1422+231 was obtained with the IR detector array mounted on the KPNO 4 m telescope by Kawara et al. (1996). The observed Fe II (UV + optical)/Mg II \( \lambda \lambda 2796, 2804 \) flux ratio is 12.2 \pm 3.9,\(^4\) which is comparable with 8.9 derived from the composite spectrum of intermediate-redshift quasars at \( z = 1–2 \) (the Large Bright Quasar Survey; Francis et al. 1991) and 7.8 \pm 2.6 for nine low-redshift quasars at \( z = 0.15–0.63 \) (Wills et al. 1985). Using photoionization models where important excitation processes are all included, Wills et al. (1985) showed that within the wide range of physical parameters in their solar abundance models the Fe II/Mg II flux ratio is firmly bounded between 1.5 and 4, with a typical value of 3 for the likely optical depth \( \tau(BaC) = 0.5–1 \) of the hydrogen Balmer continuum. Therefore, the observed strength of Fe II emission from their sample yields an overabundance of Fe by a factor of 3 with respect to Mg (see also Netzer & Wills 1983; Collin-Souffrin, Hameury, & Joly 1988). Accordingly, with a reasonable assumption of Fe II/Mg II \( \propto \) Fe/Mg, the flux ratio for B1422+231 leads to an abundance ratio of [Mg/Fe] \(-0.61^{+0.12}_{-0.16}, 0.10^{+0.20}_{-0.12}, ([Mg/Fe] \equiv \log (Mg/Fe) - \log (Mg/Fe)_{\odot}) \), where the first errors quoted correspond to the uncertainties in transforming the flux to abundance ratio and the second to the observational errors in measuring the flux ratio. Throughout this paper we use the transformation formula \( [\text{Fe II}/\text{Mg II}]_{\odot} = 3_{-1}^{+1} \) for the uncertainty, especially in the direction of giving a larger [Mg/Fe] (or smaller age) of B1422+231 is easily exceeded by the combined uncertainties of the flux measurement and chemical evolution model that will be discussed below (see Table I).

Figure 1 shows the Fe II/Mg II flux ratio (upper panel) and the logarithmic iron abundance [Fe/H] (lower panel) as a function of time in units of Gyr. Using the Salpeter IMF and the nucleosynthesis prescriptions as described above, we calculate the standard model \( \rho_{\pi} = 7.6 \) Gyr\(^{-1} \); thick line) together with the lower SFR model \( \rho_{\pi} = 6.7 \) Gyr\(^{-1} \); dashed line). The Fe II/Mg II flux ratio is initially maintained at a low level reflecting the low Fe/Mg abundance ratio in the SN II ejecta and then starts to increase with the enhanced Fe supply because of the onset of SNe Ia from 1 Gyr until 3 Gyr. Thereafter, the Fe II/Mg II flux ratio declines, because the metal-deficient gas having the low Fe/Mg abundance ratio of genuine SN II origin is released in the interstellar matter from the surface of low-mass stars, with lifetimes greater than 3 Gyr, that were born in the initial burst of star formation. The horizontal line in the upper panel is the observed Fe II/Mg II flux ratio for B1422+231, and the shaded region brackets the range of the errors.

The intersection between the theoretical curve by the stan-
standard model and the horizontal line representing the observed Fe III/Mg II flux ratio in the upper panel gives the age of 1.50 Gyr for B1422+231, which, according to the lower panel, requires [Fe/H] = +0.96 at that age. This high metallicity of 10 times solar agrees well with the result derived by Hamann & Ferland (1992, 1993) from the N v/C iv and N v/He ii line ratios of high-redshift QSOs with z = 2–4.

We have examined the uncertainty of the estimated age and metallicity by repeating the calculations with different values of input parameters from our standard choice. Table 1 tabulates Δt = t (changed) − t (standard) for each of the changed parameters and shows that the standard model already uses the parameter values that result in a relatively low estimate of the age. Use of a higher A(SN Ia) in the model makes this age smaller by ~0.1 Gyr, thus imposing a lower bound of 1.3 Gyr, if the uncertainties of the observed Fe III/Mg II flux ratio is taken into account. This result can be applied unless A(SN Ia) in the BLRs is drastically larger than the value constrained in the solar neighborhood.

4. COMPARISON WITH THE EXPANSION AGE OF THE UNIVERSE

Consider a galaxy at redshift z, which is assumed to form at zF. The age of this galaxy is the time taken by the universe to expand from zF to z. Because of its high redshift of z = 3.62, the lower age bound of 1.3 Gyr for B1422+231 constrains not only the cosmological parameters but also the epoch of galaxy formation. Figure 3 shows the (Ω0, H0) plane with (Ω0 = 0.2, H0 = 0; middle panel), and a flat, Λ-dominated universe (Ω0 = 0.2, H0 = 0.8; right panel). Solid lines in each panel denote the result for H0 = 60 (upper line) and 80 (lower line) km s⁻¹ Mpc⁻¹, assuming zF = 10. For the purpose of comparison, the result for zF = 5 and H0 = 60 km s⁻¹ Mpc⁻¹ is shown by the dashed line.

Figures 2 and 3 indicate that the age discrepancy, now encountered at z = 3.62 in the Einstein–de Sitter universe, is alleviated either in an open, Ω0 ≲ 0.2, universe with zF ≈ 10, or in a flat, Ω0 ≲ 0.2, universe with zF ≈ 6–7. With an age set at the lower bound of 1.3 Gyr, we obtain two solutions for two different ranges of zF. However, with an age of 1.5 Gyr as obtained with our standard model, an open universe becomes difficult unless Ω0 ≲ 0.1 and zF ≈ 10.

We note that the IMF in the star-bursting phase is considered to have a shallower slope (Contini, Davoust, & Considère 1995) and/or a larger m (Rieke et al. 1993) than in the quiescent solar neighborhood. Such an IMF weighted toward massive stars was also derived from the N/C ratio in the BLRs (Hamann & Ferland 1992, 1993). If this were the case in B1422+231, a longer age, exceeding even 1.5 Gyr, is required to reach the observed Fe III/Mg II flux ratio (see Table 1). The existence of such an old galaxy at z = 3.62 would rule out an open universe, and nonzero Λ would have to be invoked. More Fe III/Mg II observations in high-redshift QSOs are evidently needed.
The interesting possibility of a requirement for nonzero-Λ has recently received some support from new distance determinations to SNe Ia discovered near z = 1 (Perlmutter et al. 1998; Garnavich et al. 1998).

5. CONCLUSION

Detailed models of chemical enrichment are used to estimate the age of a gravitationally lensed quasar B1422+231 (z = 3.62) from the Fe II/Mg II flux ratio. Our standard model, which matches the data, requires an age of 1.5 Gyr with a lower bound of 1.3 Gyr, whereas the Einstein–de Sitter universe (Ω₀ = 1, Λ₀ = 0) is 0.6–0.8 Gyr old at that redshift with current estimates of the Hubble constant H₀ = 60–80 km s⁻¹ Mpc⁻¹. This problem of the age discrepancy, now encountered at z = 3.62, was first identified at z ≈ 0 by dating the GCs (15.8 ± 2.1 Gyr, Bolte & Hogan 1995: 14.56 ± 2.49 Gyr, Chaboyer et al. 1996) and the radioactive element Th in a very old halo star (CS22892−052; 15.2 ± 3.7 Gyr, Cowan et al. 1997) and then at z = 1.55 by dating the UV to optical spectral energy distribution for a high-redshift radio galaxy LBDS 53W091 (≈3.5 Gyr, Spinrad et al. 1997).

In finding potential ways to remove the age discrepancy of the GCs, a brighter RR Lyrae calibration of Mₚ (RR) ≈ +0.2 mag, and therefore younger GC ages, was inferred from Hipparcos measurements of parallaxes of Galactic Cepheids (Feast & Catchpole 1997) and Galactic metal-poor subdwarfs (Reid 1997). However, an analysis of Hipparcos proper motions and parallaxes of Galactic RR Lyraes by Tsujimoto, Miyamoto, & Yoshii (1998) directly confirmed Mₚ (RR) ≈ +0.6 mag, as was previously accepted. Therefore, the age discrepancy of the GCs is not yet resolved.

The age discrepancy at z = 3.62 in this paper is based on the Fe/Mg abundance ratio derived from a simple scaling of their emission line fluxes and therefore needs to be confirmed by more detailed modeling of the emission line transfer of Fe II in the BLR using the newly available atomic data (e.g., Sigut & Pradhan 1998). In this regard, although the present analysis already suggests a nonzero-Λ universe (see Fig. 3), a definitive discrimination between an open universe and a nonzero-Λ universe awaits future efforts of elaborating the photoionization model as well as observing the Fe II/Mg II flux ratio in more QSOs at z ~ 3–5, because no other age-dating methods except for the nucleosynthesis clock are able to be employed at such a great distance and early epoch in the universe.

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