Cosmological implications of APM 08279+5255, an old quasar at $z = 3.91$

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ABSTRACT

The existence of old high-redshift objects provides an important tool for constraining the expanding age of the Universe and the formation epoch of the first objects. In a recent paper, Hasinger et al. (2002) reported the discovery of the quasar APM 08279+5255 at redshift $z = 3.91$ with an extremely high iron abundance, and estimated age of 2 - 3 Gyr. By assuming the lower limit for this age estimate and the latest measurements of the Hubble parameter as given by the HST key project, we study some cosmological implications from the existence of this object. In particular, we derive new limits on the dark matter and vacuum energy contribution. Our analysis is also extended to quintessence scenarios in which the dark energy is parameterized by a smooth component with an equation of state $p_x = \omega_x \rho_x$ ($-1 \leq \omega_x < 0$). For flat models with a relic cosmological constant we show that the vacuum energy density parameter is constrained to be $\Omega_{\Lambda} \geq 0.78$, a result that is marginally compatible with recent observations from type Ia supernovae (SNe Ia) and cosmic microwave background (CMB). For quintessence scenarios the same analysis restricts the cosmic parameter to $\omega_x \leq -0.22$. Limits on a possible first epoch of quasar formation are also briefly discussed. The existence of this object pushes the formation era back to extremely high redshifts.

Key words: Cosmology: theory - dark matter - distance scale

1 INTRODUCTION

An impressive convergence of recent observational results seems to rule out with great confidence a large class of cold dark matter (CDM) universes. To reconcile these observational evidence with theory, cosmologists have proposed more general models whose basic ingredient is a negative-pressure dark component. The existence of such a “dark energy” not only explains the accelerated expansion of the Universe observed from luminosity distance measurements (Perlmutter et al. 1999; Riess et al. 1998) but also reconciles the inflationary flatness prediction ($\Omega_{\text{Total}} = 1$) with the dynamical estimates of the quantity of matter in the Universe which consistently point to $\Omega_m = 0.3 \pm 0.1$ (Calberg et al. 1996). From a large variety of independent techniques, the best-fit cosmological model with the dark energy component represented by a cosmological constant ($\Lambda$CDM) has $\Omega_m \sim 0.3$ and $\Omega_{\Lambda} \sim 0.7$ (Peebles & Ratra 2002; Padmanabhan 2002). If one assumes that the dark energy is parameterized by a more general equation of state, say, $p_x = \omega_x \rho_x$ with $-1 \leq \omega_x < 0$ (Turner & White 1997; Chiba et al. 1997) several analyses suggest $\Omega_x \sim 0.7$ ($\Omega_m \sim 0.3$) and $\omega_x < -0.6$ as the best-fit quintessence scenario (see Kuijla et al. 2002 and references therein). It is believed that with the new generation of observational projects not only a more accurate determination of the main cosmological parameters but also a discrimination between general quintessence models and $\Lambda$CDM scenarios ($\omega_x = -1$) will be possible.

On the other hand, if the presence of a dark energy component is necessary in order to fit observational results with theoretical predictions, its nature still remains a completely open question giving rise to the so-called dark energy problem. In this way, an important task nowadays in cosmology is to find new methods or to revive old ones in order to quantify the amount of dark energy present in the Universe, as well as to determine its equation of state and/or its time dependence. In this concern, the recent discovery of a 2-Gyr-old quasar at a redshift of $z = 3.91$ is therefore a particularly interesting event. Its existence is important to study the effect of a cosmological constant or a quintessence component on the age of the Universe at high-$z$ (Kennicutt Jr. 1996; Krauss 1997). In principle, together with other re-

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cent age determinations of high-z objects (Stockton et al. 1995; Dunlop et al. 1996; Dunlop 1998; Yoshii et al. 1998) a relevant statistical analysis may be developed near future, thereby providing restrictive constraints on any realistic cosmological model.

In the present work we study some cosmological implications from the existence of the quasar APM 08279+5255. Although considering the existence of several candidates to dark energy (Ratra and Peebles 1988; Carvalho et al. 1992; Dev et al. 2002; Sahni and Shtanov 2002; Alcaniz 2002; Zhu and Fujimoto 2002) we focus our attention to ΛCDM and X-matter models (Turner and White 1997). In particular, we analyze the constraints on the cosmological parameters Ωx and ωx from the age estimates of this object (Hasinger et al. 2002; see also Komossa & Hasinger 2002). The main aim here is to convert the estimated lower bounds on the dimensionless age parameter for this object to lower (upper) limits on Ωx. Some possible constraints on the first epoch of quasar formation are also discussed. Our approach is based on Alcaniz & Lima (1999; 2001).

2 AGE-REDSHIFT TEST

The age-redshift relation for a spatially flat, homogeneous, and isotropic cosmologies with an extra smooth component (p_x = ω_xρ_x) reads

\[ t_z = \frac{1}{H_0} \int_0^{(1+z)^{-1}} \frac{dx}{x \sqrt{\Omega_m x^{-1} + \Omega_x x^{-3(1+\omega_x)}}} \]

\[ = H_0^{-1} f(\Omega_m, \Omega_x, \omega_x, z). \]  

(1)

Note that for \( \omega_x = -1 \) the above expression reduces to the well known result for ΛCDM scenarios (\( \Omega_x \equiv \Omega_\Lambda \) whereas for \( \omega_x = 0 \) the standard relation, \( t_z = \frac{1}{3} H_0^{-1}(1+z)^{-3/2} \), is readily recovered. As can be easily seen from the above equation limits on the cosmological parameters \( \Omega_x \) and \( \omega_x \) can be readily obtained by fixing the product \( H_0 t_z \) from observations. Note also that such an age parameter depends only on the product of the two quantities \( H_0 \) and \( t_z \), which are measured from completely independent methods. To clarify these points, in what follows we briefly outline our main assumptions for this analysis.

Following standard lines, we take for granted that the age of the Universe at a given redshift is bigger than or at least equal to the age of its oldest objects. As one may conclude, for quintessence or ΛCDM scenarios, the comparison of these two quantities implies a lower (upper) bound for \( \Omega_x \) (\( \omega_x \)), since the age of the Universe increases (decreases) for larger values of this quantity. In order to quantify these qualitative arguments, it is convenient to introduce the ratio (Alcaniz & Lima 1999)

\[ \frac{t_z}{t_\Omega} = f(\Omega_m, \Omega_x, \omega_x, \Omega_\Lambda) \geq 1, \]  

(2)

where \( t_\Omega \) is the age of an arbitrary object, say, a quasar or a galaxy at a given redshift \( z \) and \( f(\Omega_m, \omega_x, \Omega_\Lambda) \) is the dimensionless factor defined in Eq. (1). For each object, the denominator of the above equation defines a dimensionless age parameter \( T_\Omega = H_0 t_\Omega \). In particular, for the 2.0-Gyr-old quasar at \( z = 3.91 \) yields \( T_\Omega = 2.0 H_0 \) Gyr which, for the most recent determinations of the Hubble parameter,

\[ H_0 = 72 \pm 8 \text{ km s}^{-1} \text{Mpc}^{-1} \]  

(Freedman et al. 2001), takes values on the interval \( 0.131 < T_\Omega < 0.163 \). It follows that \( T_g > 0.131 \). Therefore, for a given value of \( H_0 \), only models having an expanding age bigger than this value at \( z = 3.91 \) will be compatible with the existence of this object. In particular, taking \( \omega = 0 \) (the standard flat case) in Eq. (1), one obtains \( t_\Omega < 0.061 \), which means that the Einstein-de Sitter model is formally ruled out by this test with great confidence (Komossa & Hasinger 2002). In order to assure the robustness of our analysis, we will adopt in our computations the lower bound for the above mentioned value of the Hubble parameter, i.e., \( H_0 = 64 \text{ km s}^{-1} \text{Mpc}^{-1} \).

To what extent does the Hasinger et al. (2002) result provide new constraints on the cosmological parameters \( \Omega_\Lambda \) and \( \omega_x \)? To answer this question in Figs. 1a and 1b we show the dimensionless age parameter \( T_\Omega = H_0 t_\Omega \) as a function of the redshift for several values of \( \Omega_\Lambda \). The shadowed regions in the graphs were determined from the minimal value of \( T_\Omega \). It means that any curve crossing the rectangles yields an age parameter smaller than the minimal value required by the presence of the quasar APM 08279+5255. We see from Fig. 1a that by assuming an age estimate of 2 Gyr the minimal value for the vacuum energy density is \( \Omega_\Lambda, \Omega_\Lambda > 0.78 \), which provides, for the above considered Hubble parameter interval, a minimal total age of \( 12.8 - 16.0 \) Gyr. This value of \( \Omega_\Lambda \) is only marginally in accordance with most of the recent observational data which seem to point out to a flat universe with \( \Omega_\Lambda \approx 0.7 \) (see, for example, Peebles & Ratra 2002 for a recent review). We recall at this point, in line with the arguments presented by Komossa & Hasinger (2002), that recent x-ray observations show an Fe/O ratio

\[ 0.1 \leq \frac{N_{\text{Fe}}}{N_{\text{O}}} \leq 0.2. \]
for the quasar APM 08279+5255 that is compatible with an age of 3 Gyr. In this case, Fig. 1b shows that the minimal value of Ω_X required in order to make flat ΛCDM scenarios compatible with the existence of this object is 0.91. Such a lower limit is much higher than the value that can be inferred from an elementary combination of CMB measurements pointing to Ω_{Total} = 1.1 ± 0.07 (de Bernardis et al. 2000; Jaffe et al. 2001) and clustering estimates giving Ω_m = 0.3 ± 0.1 (Calberg et al. 1996) or from a rigorous statistical analysis involving many astrophysical constraints (Harun-or-Rashid & Roos 2001). Naturally, we do not expect such results to be free of observational and/or theoretical uncertainties (see, for example, Hamann & Ferland 1993 and Chartas et al. 2002)\(^1\). However, if independent analyses confirm such estimates the existence of this quasar brings to light a new consistency problem between this particular result and several others discussed recently in the literature.

Figure 2 shows a similar analysis for quintessence scenarios. Now, instead of plotting the age-redshift diagram for these models we show the parameter space in which contours represent the minimal value of the age parameter discussed above. As can be seen, although restrictive constraints can be placed on the matter density parameter (in line with the above discussion), the upper limits on the quintessence equation of state are not so tight. This happens basically because at this redshift the age parameter is not a very sensitive function to the equation of state parameter ω_x. In particular, we found ω_x ≤ −0.22 and Ω_m ≤ 0.22 and ω_x ≤ −0.33 and Ω_m ≤ 0.09 for an age estimate of 2 and 3 Gyr, respectively. Such bounds on ω_x are very similar to that ones obtained from the age estimates of the radio galaxy LBDS 53W069 (Bruzual & Magris 1997; Yi et al. 2000; Nolan et al. 2000).

\(^1\) See also the debate involving the age estimates for the radio galaxy LBDS 53W069, LBDS 53W091 and 3C 65, although the limits on Ω_m are now much more restrictive (Lima & Alcaniz 2000). The latter aspect is particularly noticeable to the case of a cosmological constant (ω = −1). From figure 2 we see that for a ΛCDM Universe, the density parameter is just the extreme value, Ω_m = 0.22, when the lower limit of 2 Gyr is considered. However, by taking 3 Gyr as the real age of the quasar one finds the second extreme value, namely, Ω_m = 0.09. Both results disagree completely with the recent limits on Ω_m obtained from X-ray measurements of galaxy clusters (Allen et al. 2002). The main results of this analysis are presented in Table I.

### Table I. Limits to Ω_λ and ω_x

| Age estimate | Ω_λ | ω_x |
|--------------|-----|-----|
| 2.0 Gyr........ | ≥ 0.78 | ≤ −0.22 (Ω_m ≤ 0.22) |
| 3.0 Gyr........ | ≥ 0.91 | ≤ −0.33 (Ω_m ≤ 0.09) |

### Figure 3. The Ω_m − z_f plane for ΛCDM models. The contours are fixed using the age parameter H_o t_x for the quasar APM 08279+5255. The solid curve corresponds to 3 Gyr while the dashed curve represents 2 Gyr. For each contour the arrows delimit the allowed parameter space. We see that the redshift formation increases with the value of Ω_m. However, the allowed region for each curve falls below the interval (Ω_m = 0.3 ± 0.1) inferred from independent methods.

### 3 IMPLICATIONS ON THE EPOCH OF QUasar FORMATION

At this point we change the focus of our discussion to investigate possible constraints on the epoch of quasar formation from the age estimate of the quasar APM 08279+5255. In order to infer such limits we do not consider in our computations the time necessary for the quasar formation. In other words, the reasonable assumption of an incubation time will be totally neglected in our analysis. This means that any limit on the redshift formation z_f will be a conservative lower bound. For look-back time calculations, such a
hypothesis can be translated as (Alcaniz & Lima 2001)

\[ t_{\text{obs}} - t_f = \frac{H_0^{-1}}{\Omega_m^{\frac{1}{2}}} \int_{(1+z_f)^{-1}}^{(1+z_{\text{obs}})^{-1}} \frac{dx}{x^{1/2}(1+z)(1+\Omega_m x^{-3})} \]

\[ \geq t_0, \]  

(3)

where the inequality signal comes from the fact that the Universe is older than or at least has the same age of any observed structure. Since this natural argument also holds for any time interval, a finite value for the observed structure. Since this natural argument also holds for any time interval, a finite value for the age of the Universe is older than or at least has the same age of any observed structure. Since this natural argument also holds for any time interval, a finite value for the age of the universe can be obtained in a natural way.

In Fig. 3a we show the \( z_f - \Omega_m \) plane allowed by the existence of the quasar APM 08279+5255 for \( \Lambda \)CDM models. As before, two age estimates were assumed: 2 Gyr (dashed curve) and 3 Gyr (solid curve). As should be physically expected, since the effect of dark matter is decelerate the cosmic expansion\(^2\), the larger the contribution of \( \Omega_m \) the larger the value of \( z_f \) that is required in order to account for the existence of this quasar within these cosmological scenarios. In this way, the smallest value for the formation redshift occurs for a completely empty universe (\( \Omega_m = 0 \)). From Figure 3 one may see that \( z_f \geq 5 \). For a low-density universe with \( \Omega_m = 0.2 \) we obtain \( z_f \geq 40 \). As expected from the previous analysis, \( z_f \rightarrow \infty \) when the matter density parameter approaches to 0.22.

4 CONCLUSION

The problem related to the lower limits for the total age of the universe, as inferred from age estimates of globular clusters (at \( z = 0 \)), was a recurrent problem in the development of physical cosmology. In actual fact, it was a real source of progress for cosmology ever since the Hubble discovery of the expanding Universe.

In a similar vein, old high redshift objects may play an equivalent role to the question related to the ultimate fate of the Universe. Their age estimates provide a powerful technique for constraining the basic cosmological parameters. In particular, the so-called high redshift “age crisis” is now becoming an important complement to other independent cosmological tests. As we have seen, the constraints on the \( \Omega_m - \Omega_\Lambda \) plane based solely on the recent age estimates of the APM 08279+5255 quasar are very restrictive. Actually, the analysis presented here is more restrictive than the earlier results derived from age estimates of some old high redshift galaxies (Alcaniz & Lima 1999). It should be stressed that the present constraints on the formation redshift are indeed rather conservative since the lower limit on the age of the APM quasar has been considered in all the estimate and the possible Institutions time has also been neglected in the original work. Finally, these high limits on \( z_f \) are also in line with the current idea that old objects are not uncommon at very large redshifts, say, at \( z > 4 \), and also reinforce the interest on the observational search for quasars, galaxies and other collapsed objects within the redshift interval \( 6 \leq z \leq 10 \), which nowadays delimits the so-called dark zone.

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REFERENCES

Alcaniz J. S., 2002, Phys. Rev. D65, 123514
Alcaniz J. S. & Lima J. A. S., 1999, ApJ, 521, L87
Alcaniz J. S. & Lima J. A. S., 2001, ApJ, 550, L133
Allen S. W., Schmidt R. W., Fabian A. C., 2002, MNRAS, 334, L11
Bruzual G. and Magris G., AIP Conference Proceedings, v. 408, p.291, astro-ph/0207154
Carlberg R. G., et al., 1996, ApJ, 462, 32
Carvalho J. C., Lima J. A. S. and Waga I., 1992, Phys. Rev. D46, 2404
Chartas G., Brandt W. N., Gallagher S. C. and Garmire G. P., 2002, ApJ, 579, 169
Chiba T., Sugiyama N., and Nakamura T., 1997, MNRAS, 289, L5
Dev A., Jain D., and Alcaniz J. S., 2003, Phys. Rev. D67, 023515
Dunlop J. et al., 1996, Nature, 381, 581
Dunlop J., in The Most Distant Radio Galaxies, ed. H. J. A. Rottgering, P. Best, & M. D. Lehnert, Dordrecht: Kluwer, 71 (1999)
Freedman W. L., et al., 2001, ApJ, 553, 47
Hamann F. and Ferland G., 1993, ApJ, 418, 11
Harun-or-Rashid S. H. and Roos M., 2001, A&A, 373, 369
Hasinger G., Chartas G., Schartel N. and Komossa S., 2002, ApJ, 573, L77
Kennicutt Jr. R. C., 1996, Nature, 381, 555
Ko a s s a and Hasinger G., in XEUS studying the evolution of the universe, G. Hasinger et al. (eds), MPE Report, in press astro-ph/0207321
Krauss L., 1997, ApJ, 480, 466
Kujat J. et al., 2002, ApJ, 572, 1
Lima J. A. S. and Alcaniz J. S., 2000, MNRAS, 313, 893
Nolan L. A., Dunlop J. S. and Jimenez R., 2001, MNRAS, 323, 385
Padmanabhan T., 2002, hep-th/0212290
Peebles P. J. E. and Ratra B., astro-ph/0207347
Perlmutter S., et al., 1999, ApJ, 517, 565
Riess A. et al., 1998, AJ, 116, 1009
Ratra B. and Peebles P. J. E., 1988, Phys. Rev. D 37, 3406
Sahni V. and Shtanov Y., gr-qc/0205111
Stockton A., Kellog M. and Ridgway S. E., 1995, ApJ, 443, L69
Turner M. S. and White M., 1997, Phys. Rev. D, 56, R4439
Yi S. et al., 2000, ApJ, 533, 670
Yoshii Y., Tsujimoto T. and Kawara K., 1998, ApJ, 507, L133
Zong-Hong Zhu and Masa-Katsu Fujimoto, 2002, ApJ, 581, 1

\(^2\) It means that the look-back time between the observed redshift \( z_{\text{obs}} \) and \( z_f \) is smaller for larger values of \( \Omega_m \).