Are Galaxy Clusters Suggesting an Accelerating Universe Independent of SNe Ia and Gravity Metric Theory?

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A kinematic method to access cosmic acceleration based exclusively on the Sunyaev-Zel’dovich effect (SZE) and X-ray surface brightness data from galaxy clusters is proposed. By using the SZE/X-ray data from 38 galaxy clusters in the redshift range 0.14 ≤ z ≤ 0.89 [Bonamente et al., ApJ. 647, 25 (2006)], we find that the present Universe is accelerating and that the transition from an earlier decelerating to a late time accelerating regime occurred relatively recent. Such results are fully independent on the validity of any metric gravity theory, the possible matter-energy contents filling the Universe, as well as on the SNe type Ia Hubble diagram from which the present acceleration was inferred. The ability of the ongoing Planck satellite mission to obtain tighter constraints on the expansion history through SZE/X-ray angular diameters is also discussed. Two simple simulations of future Planck data suggest that such technique will be competitive with supernova data besides being complementary to it.

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Introduction. The dimming of distant type Ia supernovae observed by two different group of astronomers one decade ago lead to unexpected and landmark conclusion: the universal expansion is speeding up and not slowing down as believed since the early days of observational cosmology[1,2].

Such phenomenon is normally interpreted as a dynamic influence of some sort of dark energy whose main effect is to change the sign of the decelerating parameter q(z) [3]. Another possibility is that the cosmic acceleration is a manifestation of new gravitational physics (rather than dark energy) that involves a modification of the left hand side (geometric sector) of the Einstein field equations. In this sort of theory the Friedmann equation is modified and a late time accelerating stage is obtained even for a Universe filled only with cold dark matter (CDM) [4]. At present, the space parameter associated with the cosmic expansion is too degenerate, and, as such, it is not possible to decode which mechanism or dark energy component is operating in the cosmic dynamics [3,4].

Currently, SNe type Ia are not only the powerful standard candles available but still provides a unique direct access to the late time accelerating stage of the Universe. Naturally, this a rather uncomfortable situation from the observational and theoretical viewpoints even considering that ten years later, the main observational concerns about errors in SNe type Ia measurements, like host galaxy extinction, intrinsic evolution, possible selection bias in the low redshift sample seem to be under control [5].

A promising estimator fully independent of SNe type Ia and other calibrators of the cosmic distance ladder is the angular diameter distance (DA(z)) from a given set of distant objects. It has also been recognized that the combination of SZE [6] and X-ray surface brightness measurements may provide useful angular diameters from galaxy clusters [7,8,9,10,11].

On the other hand, since the mechanism causing the acceleration is still unknown, it is interesting to investigate the potentialities of SZE/X-ray technique from a more general viewpoint, that is, independent of the gravity theory and the matter-energy contents filling the Universe. The better strategy available so far is to consider the same kind of kinematic approach which has been successfully applied for determining the transition deceleration/acceleration in the past by using SNe type Ia measurements [12,13,14,15,16].

In this letter, we employ a purely kinematic description of the universal expansion based on angular diameter distances of clusters for two different expansions of the deceleration parameter. As we shall see, by using the Bonamente et al. sample we find that a kinematic analysis based uniquely on cluster data suggests that the Universe undergone a “dynamic phase transition” (deceleration/acceleration) in a redshift z ≈ 0.3. Further, it is also shown that the Planck satellite mission data must provide very restrictive limits on the space parameter, thereby opening an alternative route for accessing the expansion history of the Universe.

Angular Diameter and Kinematic Approach. Let us now assume that the Universe is spatially flat as motivated by inflation and WMAP measurements [17]. In this case, the angular diameter distance in the FRW metric is defined by (in our units c = 1),

\[ D_A = (1 + z)^{-1}H_0^{-1}\int_0^z du H(u) = (1 + z)^{-1}\frac{H_0}{\int_0^z \exp \left[ - \int_0^u [1 + q(u)]d\ln(1 + u) \right] du} \]  
\[ (1) \]
As one may check, in the case of a linear two-parameter expansion for the angular diameter distance, an exact expression for the trans-

Now, the integral (1) assumes the form:

\[ D_A(z) = \frac{(1+z)^{-1}}{H_0} e^{q_0 z} q_0 (q_0 + q_1) \gamma (q_1 + q_0, (1 + z)) \]

where \( q_0 \) and \( q_1 \) are the values of \( q(z) \) and its redshift derivative, \( dq/dz \) evaluated at \( z = 0 \) while \( \gamma \) is an incomplete gamma function [13]. By using the above expressions we may get information about \( q_0 \), \( q_1 \) and, therefore, about the global behavior of \( q(z) \). In principle, a dynamic “phase transition” (from decelerating to accelerating) happens at \( q(z_t) = 0 \), or equivalently, \( z_t = -q_0/q_1 \). Another interesting parametrization is \( q(z) = q_0 + q_1 z/(1 + z) \) [13, 14]. It has the advantage to be well behaved at high redshift while the linear approach diverges at the distant past. Now, the integral (1) assumes the form:

\[ D_A(z) = \frac{(1+z)^{-1}}{H_0} e^{q_0 z} q_1 \gamma (q_1 + q_0, (z+1)q_1) - \gamma (q_1 - q_0, q_1) \]

where \( q_1 \) now is the parameter yielding the total correction in the distant past \( (z \gg 0) \). Let us now consider the 38 measurements of angular diameter distances from galaxy clusters as obtained through SZE/X-ray method by Bonamente and coworkers [11]. In our analysis we use a maximum likelihood determined by a \( \chi^2 \) statistics

\[ \chi^2(z|p) = \sum_i \frac{(D_A(z_i; p) - D_{A_0;i})^2}{\sigma_{D_{A0;i}}^2 + \sigma_{stat}^2}, \]

where \( D_{A0;i} \) is the observational angular diameter distance, \( \sigma_{D_{A0;i}} \) is the uncertainty in the individual distance, \( \sigma_{stat} \) is the contribution of the statistical errors added in quadrature \((\approx 20\%)\) and the complete set of parameters is given by \( p \equiv (H_0, q_0, q_1) \). For the sake consistency, the Hubble parameter \( H_0 \) has been fixed by its best fit value \( H_0^* = 80 \text{ km/s/Mpc} \).

Constraints from Galaxy Clusters. The SZE is a small distortion on the Cosmic Microwave Background (CMB) spectrum provoked by the inverse Compton scattering of the CMB photons passing through a population of hot electrons. Observing the temperature decrement of the CMB spectrum towards galaxy clusters together the X-rays observations, it is possible to break the degeneracy between concentration and temperature thereby obtaining \( D_A(z) \). Therefore, such distances are fully independent of the one given by the luminosity distance, \( D_L(z) \).

FIG. 1: a) Contours in the \( q_0 - q_1 \) plane for 38 galaxy clusters data [11] considering \( q(z) = q_0 + q_1 z \). The best fit to the pair of free parameters is \( (q_0, q_1) \equiv (-1.35, 4.2) \). For comparison we have shown the straight lines denoting the transitions redshifts for two different \( \Lambda \)CDM models: \( z_t = 0.9 \) for \( \Omega_\Lambda = 0.8 \) and \( z_t = 0.15 \) for \( \Omega_\Lambda = 0.43 \). b) Likelihood function for the transition redshift. The best fit is \( z_t = 0.32 \).
trapezium. The horizontal line at the top is defined by $q_1 = 0$, which leads to an infinite (positive or negative) transition redshift. Note also that the segment at 45% defines the infinite future ($z_t = -1$). In addition, one may conclude that the vertical segment on the left closing the trapezium is also unphysical since it is associated $z_t \leq -1$, thereby demonstrating that the hatched trapezium is actually a physically forbidden region (for a similar analysis involving luminosity distance see [13]). For comparison we have also indicated in Fig. 1(a) the transition redshifts $z_t = 0.15$ corresponding to a flat ΛCDM with $\Omega_a = 0.43$, as well as, $z_t = 0.9$ corresponding to $\Omega_a \simeq 0.8$.

2nd Parameterization: $q = q_0 + q_1 z/(1 + z)$. In Figures 2(a) and 2(b) we display the corresponding plots for the second parameterization. The confidence region (1σ) is now defined by: $-2.4 \leq q_0 \leq -0.5$ and $13.5 \leq q_1 \leq 0$. Such results also favor a Universe with recent acceleration ($q_0 < 0$) and a previous decelerating stage ($dq/dz > 0$). As indicated in Fig. 2(a), the best fits to the free parameters are $q_0 = -1.43$ and $q_1 = 6.18$ while for the transition redshift is a little smaller $z_t = 0.3$ (see Fig. 1(b)). It should be noticed the presence of the forbidden region (trapezium) with a minor difference in comparison with Fig. 1(a), namely, as an effect of the parameterization, the horizontal line now is at the bottom. Note also that a decelerating Universe today ($q_0 > 0$) is only marginally compatible at 2σ of statistical confidence.

The results in the $q_0 - q_1$ planes for both cases suggest that: (i) The Universe had an earlier decelerating stage ($q_1 = dq/dz > 0$), and (ii) The Universe has been accelerating ($q_0 < 0$) since $z \sim 0.3$. A similar result has been previously obtained using SNe Ia as standard candles by Shapiro and Turner [12].

**Prospects for Planck Satellite Mission.** Let us discuss the potentiality of the SZE/X-ray technique when future data from Planck satellite mission become available [19]. The mission is a project from European Space Agency whose frequency channels were carefully chosen for measurements of thermal Sunyaev-Zeldovich effect. In principle, the Planck satellite will see (through SZE) about 30,000 galaxy clusters over the whole sky with a significant fraction of clusters near or beyond redshift unity. However, since accurate angular diameter measurements require long SZE/X-ray integrations nobody expects that all observed clusters might have useful distance measurements to constrain cosmological parameters. Therefore, it is interesting to simulate two realistic samples of angular diameter distances (ADD) by using a fiducial model to $D_{\text{ADD}} = D_A(z_t, q_0, q_1^*, H_0^*)$, where $H_0^*$, $q_0^*$ and $q_1^*$ are the best fit values to the linear case obtained from Bonamente et al. sample [11].

| $z$ range | Clusters | bins | Clusters/bin | ADD Error |
|-----------|----------|------|-------------|-----------|
| 0, 0.5    | 100, 500 | 10   | 10, 50      | 15%, 10%  |
| 0.5, 1.0  | 70, 350  | 10   | 7, 35       | 17%, 12%  |
| 1.0, 1.5  | 40, 200  | 10   | 4, 20       | 20%, 15%  |

The first simulation (termed pessimistic - P), assumes that only 210 clusters are distributed in the redshift ranges in the following form: $0 \leq z \leq 0.5$ (100), $0.5 \leq z \leq 1$ (70) and $1 \leq z \leq 1.5$ (40) with ADD statistical errors of 15%, 17% and 20%, respectively (see Table 1).

In the second one (optimistic case - O), 1050 clusters were redshift distributed as follows, $0 \leq z \leq 0.5$ (500), $0.5 \leq z \leq 1$ (350) and $1 \leq z \leq 1.5$ (200) with ADD statistical errors of 10%, 12% and 15%, respectively. The redshift intervals were partitioned into bins ($\Delta z = 0.05$) with the clusters distributed as shown in Table 1 [20].

Both simulations were carried out by marginalizing over the $H_0$ parameter in $D_A(z_t, p)$ in Eqs. (1) and (5).
The ability of the ongoing Planck satellite mission to constrain the accelerating stage was discussed by simulating two realistic samples of angular diameters from clusters. The allowed regions in space parameter was significantly constrained for both the pessimistic and optimistic simulations (Figure 3). The limits on the transition redshift derived here reinforces the extreme interest on the observational search for obtaining SZE/X-ray data from galaxy clusters.

Finally, we stress that the present results depends neither on the validity of general relativity nor the matter-energy contents of the Universe and, perhaps, more important, they are also independent from SNe type Ia observations.

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References

[1] A. G. Riess et al., Astron. J. 116, 1009 (1998).
[2] S. Perlmutter et al., Astrophys. J. 517, 565 (1999).
[3] T. Padmanabhan, Phys. Rep. 380, 235 (2003); P. J. E. Peebles and B. Ratra, Rev. Mod. Phys. 75, 559 (2003); J. A. S. Lima, Braz. J. Phys. 34, 194 (2004); E. J. Copeland, M. Sami and S. Tsujikawa, Int. J. Mod. Phys. D 15, 1753 (2006); J. A. Frieman, M. S. Turner and D. Huterer, Ann. Rev. Astron. & Astrophys. 46, 385 (2008).
[4] L. Amendola, David Polarski, Shinji Tsujikawa, Phys. Rev. Lett. 98, 131302 (2007); T. P. Sotiriou and V. Faraoni, arXiv:0805.1726 [gr-qc].
[5] M. Kowalski et al., Astrophys. J. 686, 749 (2008).
[6] R. A. Sunyaev and Ya. B. Zel’dovich, Astrophys. Space Sci. 7, 20 (1970); R. A. Sunyaev and Ya. B. Zel’dovich, Comments Astrophys. Space Phys. 4, 173 (1972).
[7] A. Cavaliere, L. Danese and G. De Zotti, Astrophys. J. 217, 6 (1977); A. Cavaliere, R. Fusco-Femiano, Astron. Astrophys. 70, 677 (1978); M. Birkinshaw, Mon. Not. R. Astron. Soc. 187, 847 (1979).
[8] M. Birkinshaw, Phys. Rep. 310, 97 (1999).
[9] J. G. Bartlett and J. Silk, Astrophys. J. 423, 12 (1994); J. E. Carlstrom, G. P. Holder and E. D. Reese, ARAA 40, 643 (2002); E. D. Reese et al., Astrophys. J. 581, 53 (2002); M. E. Jones et al., MNRAS 357, 518 (2002).
[10] J. V. Cunha, L. Marassi and J. A. S. Lima, MNRAS 379, L1 (2007), [astro-ph/0611934].
[11] M. Bonamente et al., Astrophys. J. 647, 25 (2006).
[12] M. S. Turner and A. G. Riess, Astrophys. J. 569, 18 (2002); C. Shapiro and M. S. Turner, Astrophys. J. 649, 563 (2006).
[13] A. G. Riess et al., Astrophys. J. 607, 665 (2004).
[14] Elgarøy, Ø., & Multamäki, T. 2006 JCAP 9; 2; A. G. C. Guimaeraes, J. V. Cunha and J. A. S. Lima, arXiv:0904.3550v1 [astro-ph.CO] (2009).
[15] J. V. Cunha and J. A. S. Lima, MNRAS 390, 210 (2008), arXiv:0805.1261.
[16] L. Xu, C. Zhang, B. Chang and H. Liu, 2007 astroph-ph/0701519v2; J. V. Cunha, Phys. Rev. D 79, 047301 (2009).
[17] E. Komatsu et al., Astrophys. J. Suppl. 180, 330 (2009).
[18] M. Abramowitz and I. A. Stegun, Handbook of Mathematical Functions, Dover Publications (1972).
[19] The Scientific Programme of Planck (Planck Collaboration), arXiv:astro-ph/0604069.
[20] M. Goliath, R. Amanullah, P. Astier, A. Goobar and R. Pain, Astron. Astrophys. 380, 6 (2001).