Test of the decaying dark matter hypothesis using the Hopkins Ultraviolet Telescope

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SCIAMA has argued[1–4] that the dark matter associated with galaxies, clusters of galaxies and the intergalactic medium consists of τ neutrinos of rest mass 28–30 eV, whose decay generates ultraviolet photons of energy $\sim m_\nu/2 \approx$ 14–15 eV. We have carried out a test of this hypothesis using the Hopkins Ultraviolet Telescope, which was flown aboard the space shuttle Columbia as part of the Astro-1 mission in December 1990. A straightforward application of Sciama's model predicts that we should have observed, from the rich galaxy cluster Abell 665, a spectral line from neutrino decay photons with a signal-to-noise ratio of ~30. We detected no such emission. For neutrinos (or any similar dark matter particle) in the mass range 27.2–32.1 eV, our observations set a lower lifetime limit significantly greater than Sciama's model requires.

The idea is based on work by several previous authors[5–7], but Sciama's theory significantly narrows the expected energy range of the decay photon and requires a lifetime for the decay of $\tau \approx 1-3\times10^{23}$ s, substantially shorter than lifetimes predicted in most standard theories of particle physics[8], but compatible with some left-right-symmetric models[9]. The severely constrained neutrino mass and lifetime result from Sciama's assumption that the decay photons are responsible for the partial ionization of the H I regions in the galaxy, as well as the ionization of the Lyman α clouds seen in the spectra of quasars at large redshifts. The short lifetime has the added benefit of making the hypothesis eminently testable.

The energy of the decay photons in Sciama's theory is only slightly above the ionization potential of hydrogen, or Lyman limit, at 13.6 eV. Consequently, a cluster of galaxies requires only a modest redshift to make the line emission expected from the decaying dark matter particles longer than the Lyman limit at 912 Å, where the interstellar hydrogen in our Galaxy becomes transparent. The Hopkins Ultraviolet Telescope (HUT) (Davidsen *et al.*, manuscript in preparation) has been optimized for spectroscopic observations in the 912–1,200-Å band (which is inaccessible to other space telescopes except for the low-resolution spectrometer on Voyager), and is therefore ideal for searching for the predicted neutrino decay line in clusters with redshifts $z \leq 0.5$. The full spectral range covered by HUT is 830–1,850 Å in first order. HUT also includes a large aperture (17 × 116 arcsec) which projects to a substantial volume within a typical cluster and therefore yields a strong signal for the predicted neutrino decay line.

We selected several rich clusters in the range $0.1 \leq z \leq 0.2$ for observation with HUT on the Astro-1 mission, but because of Spacelab system-level problems and a weather-related shortening of the mission, only one of these clusters, Abell 665, was successfully observed.

Abell 665 is the richest cluster in the Abell catalogue[10] and a luminous X-ray source[11,12]. A recent study[13] yields $z = 0.18144 \pm 0.00084$ and a velocity dispersion $\sigma = 1{,}201^{+183}_{-126}$ km s^{-1} for 33 galaxies that were found to be cluster members. We assume the projected mass density of the cluster, including both the luminous and dark matter, follows a King model[14] of the form $\mu(r) = 2r_c\rho_0(1+r^2/r_c^2)^{-1}$ with a core radius $r_c = 0.5$ Mpc (ref. 15). The central mass density is then $\rho_0 = 1.7\times10^8\,\sigma^2/r_c^2\,M_\odot\,\mathrm{Mpc}^{-3} = 1.0\times10^{15}\,M_\odot\,\mathrm{Mpc}^{-3}$. The total mass integrated over the large HUT slit, which covered 68 × 457 kpc at the centre of Abell 665, is $2.9\times10^{13}\,M_\odot$. (We assume $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = \frac{1}{2}$ throughout.)

The uncertainties in this mass estimate contribute a large fraction of the uncertainty in our final result. Although Oegerle *et al.*[13] find no evidence for substructure in their distribution of velocities for the galaxies in Abell 665, two separate dynamical systems with dispersions of 900 km s^{-1} and mean velocities separated by 400 km s^{-1} could reproduce their data. This would lower our mass estimate by a factor of two. On the other hand, the central density and the core radius are not tightly constrained by the available data, and the mass enclosed by the HUT slit could well be higher than we have assumed.

If the mass of Abell 665 is predominantly made up of decaying neutrinos, the luminosity of the cluster is $L = 4.0\times10^{54}\,M_{13}\tau_{23}^{-1}$ $(\varepsilon/14\,\mathrm{eV})^{-1}$ photons s^{-1} in a line at energy ε, where M_{13} is the total mass in units of $10^{13}\,M_\odot$, and τ_{23} is the decay lifetime in units of 10^{23} s. The expected width of the decay line is 11 Å (full width at half maximum, FWHM), or 22 pixels, assuming the neutrino decay emission fills the HUT aperture and that the neutrinos have the velocity dispersion quoted above for the cluster. With the mass obtained above, the predicted flux at Earth is $0.089\,\tau_{23}^{-1}\,(\varepsilon/14\,\mathrm{eV})^{-1}$ photons cm^{-2} s^{-1}. In the relevant energy range HUT has an effective area of 8.0 cm^2, leading to an expected count rate of 0.24–0.71 counts s^{-1} for Sciama's proposed range for the lifetime $\tau \approx 1\text{-}3\times10^{23}$.

Abell 665 was observed with HUT for a total of 1,932 s on 9 December 1990. The aperture was centred at right ascension $\alpha_{1950} = 8$ h 26 min 24.6 s, declination $\delta_{1950} = +66°\,00'\,36.0''$, which corresponds to the position of the brightest cluster galaxy (W. Oergerle, personal comm.). Beers and Tonry give the median galaxy position[16] as $\alpha_{1950} = 8$ h 26 min 18.7 s, $\delta_{1950} = +65°\,59'\,58''$, and the centroid from the Imaging Proportional Counter on Einstein as $\alpha_{1950} = 8$ h 26 min 27.7 s, $\delta_{1950} = +66°\,01'\,07''$. The HUT slit was oriented at a position angle of 40° to include both the X-ray centre and the median galaxy position. Most of the

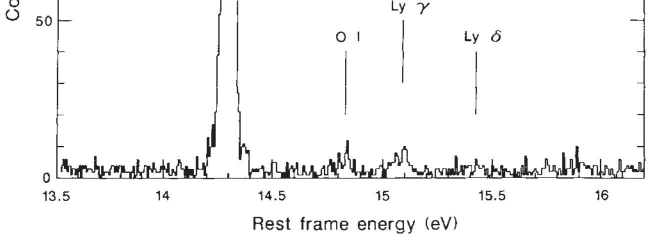

FIG. 1 Portion of the Abell 665 spectrum from the full 1,932-s observation covering the rest-frame energy range 13.6-16.1 eV. The ordinate is in observed counts per 0.51 Å bin. Prominent airglow features observed in other HUT spectra are marked.

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observation (1,378 s) was during orbital night, when airglow line emission is a minimum. The spectrum obtained had no features other than those expected from the airglow based on observations of other faint sources and blank fields during the Astro-1 mission. Figure 1 shows the relevant portion of the data from the full 1,932-s observation, corrected to the rest-frame of Abell 665. The positions of the known airglow lines Ly β, O I at 989 Å, Ly γ, and Ly δ are indicated. The observed flux of the Ly β line is 0.58 counts s^{-1}, essentially equal to the flux expected for the neutrino decay line. The background count rate (the apparent continuum in Fig. 1) of 1.2×10^{-3} per pixel per s is consistent with that from other blank sky observations. About one-third of this rate is due to internal detector background from charged particles (as measured with the aperture closed), and two-thirds is from grating-scattered geocoronal Ly α.

Emission lines from an extended source filling the $17'' \times 116''$ slit have a FWHM of 5.5 Å (11 pixels), as measured from other observations of bright airglow lines through this aperture. The Ly β line in Fig. 1 has a FWHM of 5.7 Å. As mentioned previously, emission from decaying neutrinos broadened by the cluster velocity dispersion would produce a line with FWHM 11 Å (22 pixels). At each pixel in the spectrum, we calculate upper limits to the intensity of an unresolved spectral feature at that location by computing the flux above the background in a surrounding 19-pixel region. This choice of size maximizes the signal-to-noise ratio for detecting a weak feature above the background and is conservative, as colder neutrinos would produce a narrower line which would be easier to detect. The 2σ upper limit is then $[\sum (C_i - B) + 2\sqrt{\sum C_i}]/0.71t$, where B is the background count per pixel, C_i is the number of counts in pixel i, t is the total integration time, and the factor 0.71 is the fraction of the line flux contained in the 19-pixel region. Because this sum averages ~45 counts, the Poisson count distribution closely resembles a gaussian in its statistical properties, and we have simply used a factor of twice the Poisson standard deviation.

The only spectral features that exceed these upper limits during the orbital night portion of the observation are Ly β and Ly γ. In the full observation shown in Fig. 1, airglow features due to O I at 989 Å and Ly δ are also visible, and to be conservative we have used the higher fluxes seen for the whole observation in computing our upper limits. We have not yet developed a detailed model of the expected intensity of airglow features in the HUT spectra for the many relevant parameters, such as orbital position and viewing angle relative to the Earth limb and the Sun. Emission from decaying neutrinos could (fortuitously) lie at the same wavelength as Ly β or Ly γ, but as none of the airglow features are broader than the instrumental response, the dispersion of the decaying neutrinos in the cluster would have to be much less than the observed cluster velocity dispersion.

The Ly β line is bright enough that we can set a more stringent limit using the shape of the line profile and the Ly β/Ly α ratio from other observations. To be conservative, we compute the expected Ly β flux using the lowest observed ratio of Ly β/Ly α in the airglow observed by HUT. This comes from an observation of the Crab Nebula. (The Crab was within a few degrees of the anti-solar position on the sky, and the viewing angle during orbital night was almost entirely in the Earth's shadow.) We therefore presume that any contribution from decaying neutrinos to the observed Ly β in our observation of Abell 665 can be at most the amount by which the observed flux exceeds this minimum. Within three pixels of the centre of the Ly β line, we determine our upper limit by subtracting the observed Ly β/Ly α ratio of $(2.47 \pm 0.23) \times 10^{-3}$ in the orbital night portion of the Crab Nebula spectrum from the ratio $(4.03 \pm 0.16) \times 10^{-3}$ observed during orbital night on Abell 665. Scaling this to the Ly α intensity of 116 counts s^{-1} during orbital night in the Abell 665 observation, we obtain a maximum contribution to the Ly β intensity of 0.181 ± 0.033 counts s^{-1}. We use 0.247 counts s^{-1} as our 2σ upper limit within three pixels of the Ly β line centre. The Ly β/Ly α ratio observed in the Abell 665 spectrum is typical of that seen in other orbital night observations of the airglow. We may be able to reduce the upper limits at the Ly β line centre as we develop our understanding of the airglow spectrum.

To eliminate the possibility that the decay line could be hiding in the wings of geocoronal Ly β, we compare the Ly β line profile in the Abell 665 spectrum with that observed in other night observations of weak sources. Using a Ly β line profile obtained from observations of the Crab Nebula and the Perseus cluster, summed and smoothed with a three-point boxcar, we fit a 120-pixel region centred on Ly β in the Abell 665 spectrum, allowing the line centre, its intensity and a constant background to vary freely. The resulting $\chi^2 = 126.40$ indicates excellent agreement between the profiles of the template and the Ly β line of Abell 665. The shift in wavelength between the two lines is less than one pixel. We then add a second emission line at a fixed offset which is an integral number of pixels from the centre of the Ly β emission line. The intensity of the second emission line is increased until $\Delta\chi^2 = 4.2$ (95.4% confidence for one interesting parameter[17]) while all other parameters are re-optimized. This sets our 2σ upper limit in the regions 2–11 pixels above and below the centre of the Ly β emission line.

We have converted our upper limits on the decay-line intensity for Abell 665 to a lower limit on the lifetime of the neutrino, taking into account the variation in HUT sensitivity with energy (known to ±20% over the wavelength range of interest from laboratory calibrations and in-flight comparison of several white dwarf spectra to theoretical models; P. Bergeron, personal communication) and galactic extinction of $E_{B-V} = 0.034$ for a galactic neutral hydrogen column density[18,19] of 4.7×10^{20} cm^{-2}. We use the extinction law produced by Longo *et al.*[20] from an earlier review[21]. Figure 2 shows the result, along with the range of lifetimes and energies predicted by Sciama's theory. Over most of the range of interest the observational limit on the lifetime exceeds 3×10^{24} s, a factor at least 10 times the value required by the decaying dark matter hypothesis. However, a narrow region of parameter space at $E = 14.30 \pm 0.02$ eV, where interference from geocoronal Ly β is severe, would allow the theory to survive, if we have been so unfortunate as to choose a cluster whose redshift hides the neutrino decay line behind geocoronal Ly β. (The error in E is dominated by the uncertainty in the redshift of the cluster.) We expect that detailed analysis of the

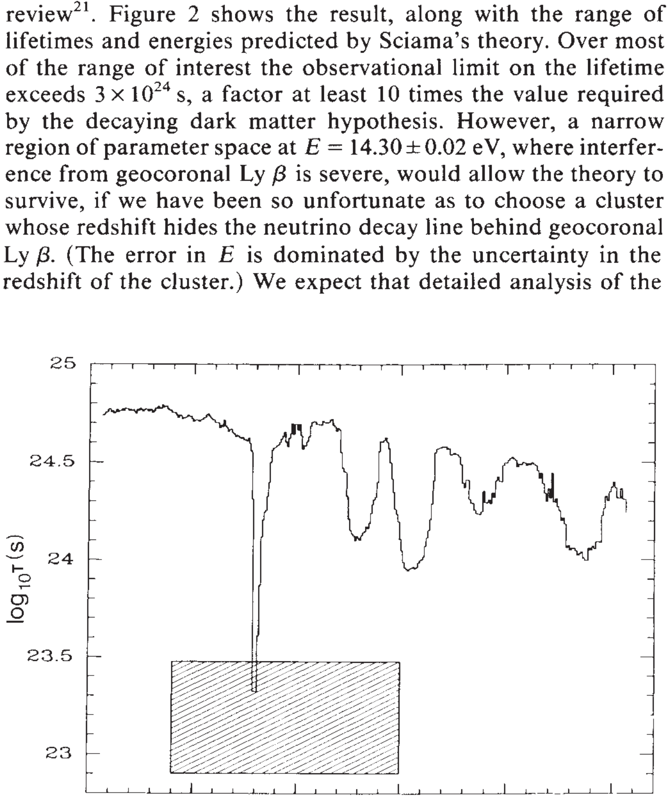

FIG. 2 Logarithm of the 2σ lower limits derived from HUT observations for the lifetime of decaying neutrinos (in s) as a function of the decay photon energy (in eV). The shaded region illustrates the range of energies and lifetimes compatible with Sciama's theory.

airglow data obtained by HUT throughout the Astro-I mission, together with further modelling, will allow us to strengthen our limit in the vicinity of Lyman β.

Highly sensitive observations of the cluster Abell 665 with the HUT thus fail to support the decaying dark matter hypothesis. The theory can survive only under one of the two following conditions: (1) the cluster is several times less massive than we estimate and the redshifted decay photon energy happens to coincide with the Ly β airglow line, or (2) there is substantial absorption of the decay line by previously unsuspected material along the line of sight. The latter has in fact been suggested by Sciama (personal communication) in response to our result. We believe we can rule out this possibility, but a discussion must be postponed to a future paper (G.A.K., A.F.D. and H.C.F., in preparation). Although neutrinos may yet provide the missing mass, they probably do not decay at rates high enough to explain the ionization balance in the interstellar or intergalactic medium. ☐

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Detection of binaries in the core of the globular cluster M15 using calcium emission lines

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M15 is the prototypical collapsed-core globular cluster. Having undergone collapse, its core is believed now to be expanding, with energy for the re-expansion provided by binary stars, which turn gravitational potential energy into kinetic energy[1]. Because these binary stars are generally more massive than single stars, they will have settled to the centre of the cluster[2]. We report here that several of the stars at the core of M15 show Ca II H- and K-line emission, characteristic of young, rapidly rotating stars and close binaries[3]. We argue that the emission from M15 comes from primordial binaries, in which a period of spin-up has led to magnetic field generation by enhanced dynamo action, which in turn causes heating of the stellar chromospheres. If this interpretation is correct, the Ca H and K emission may provide an important diagnostic tool of the binary population in cluster cores, and thus of the cluster dynamics.

Our observations were taken at the Isaac Newton Group of Telescopes on La Palma using the 4.2-m William Herschel telescope, equipped with the ISIS triple spectrograph, on the nights of 8, 11 and 13 August 1990. The blue camera and CCD-IPCS (charge-coupled device-image photon counting system) in combination with the H2400B grating gave us a dispersion of 8 Å mm^{-1} and a resolution of 0.4 Å (5 pixels full width half maximum, FWHM). Spatial sampling along the slit was 0.3″ per pixel, the final resolution at the detector was 1.1″ FWHM. Although we did not spatially resolve the three stars in the core, AC214, 215, and 216 (ref. 4), as shown in the contour plot in Fig. 1 from a blue Canada-France-Hawaii telescope CCD image taken in 0.4″ seeing (P.M.L. *et al.*, manuscript in preparation), the light at these wavelengths is dominated by the bluest objects. The seeing on the night of 8 August was 1.2″ to 1.5″. On the nights of 11 and 13 August the seeing was better than 0.7″ FWHM as measured on the spectrograph slit jaws.

Figure 2*a* shows a 40-min spectrum of a 3.0″ × 1.0″ area centred on the bluest of three stars in the central core: AC214 ($V = 14.75$, $B - V = 0.10$ (ref. 4)). Figure 2*b* shows the spectrum of the star AC623 ($V = 13.50$, $B - V = 1.04$ (ref. 4)), which is located 16″ from the centre. In both cases emission in the cores of the Ca II

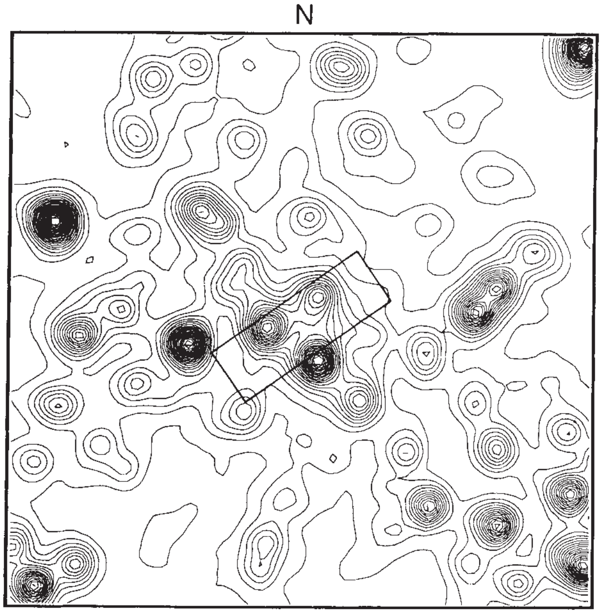

FIG. 1 A B-band image of the central 10″ × 10″ of M15 taken in September 1989 using the image-stabilization, high-resolution camera on the Canada-France-Hawaii telescope (P.M.L. *et al.*, manuscript in preparation). The pixel size is 0.11″. The box in the centre of the diagram shows the position of the slit for the spectra in Fig. 2*a*.