The Detection of a Population of Submillimeter-Bright, Strongly Lensed Galaxies
Mattia Negrello, et al.
Science 330, 800 (2010);
DOI: 10.1126/science.1193420

If you wish to distribute this article to others, you can order high-quality copies for your colleagues, clients, or customers by clicking here.

Permission to republish or repurpose articles or portions of articles can be obtained by following the guidelines here.

The following resources related to this article are available online at www.sciencemag.org (this information is current as of January 17, 2012):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:
http://www.sciencemag.org/content/330/6005/800.full.html

Supporting Online Material can be found at:
http://www.sciencemag.org/content/suppl/2010/11/03/330.6005.800.DC1.html

This article appears in the following subject collections:
Astronomy
http://www.sciencemag.org/cgi/collection/astronomy
The Detection of a Population of Submillimeter-Bright, Strongly Lensed Galaxies

Mattia Negrello,14 R. Hopwood,1 G. De Zotti,2,3 A. Cooray,4 A. Verma,5 J. Bock,6,7 D. T. Frayer,8 M. A. Gurwell,9 A. Omont,10 R. Neri,11 H. Dannerbauer,12 L. L. Leeuw,13,34 L. E. Barton,14 J. Cooke,14 S. Kim,1 E. da Cunha,15 G. Rodighiero,16 P. Cox,17 D. G. Bonfield,18 M. J. Jarvis,19 A. F. Barth,20 C. Castiaux,20 J. Zmuidzinas6,7 P. P. van der Werf,19,55 J. Zmuidzinas6,7 E. Pascale,20 M. Pohlen,20 E. E. Rigby,24 C. Simpson6 D. J. B. Smith,24 E. Barton,14 A. Beelen34 A. Blain,7 A. J. Baker,41 M. Birkinhshaw,41 R. Blundell,6 C. M. Bradford,6,7 D. Burgarella,43 L. Danese,1 J. S. Dunlop,18 S. Fleuren,14 J. Glenn,49 A. I. Harris,49 J. Kamenetzky,49 R. E. Lupi,40 R. J. Maddalena,6,7 B. F. Madsen,47 P. R. Maloney,45 H. Matsuhara,48 M. J. Maiożewski,19 E. J. Murphy,49 B. J. Naylor,6 H. Nguyen,4 C. Popescu,50 S. Rawlings,6 D. Rigopoulou,5,51 D. Scott,4 K. S. Scott,46 M. Seibert,47 I. Smail,53 R. J. Tuffs,54 J. D. Vieira,7 P. P. van der Walt19,55 J. M. Zmuidzinas,6

Gravitational lensing is a powerful astrophysical and cosmological probe and is particularly valuable at submillimeter wavelengths for the study of the statistical and individual properties of dusty star-forming galaxies. However, the identification of gravitational lenses is often time-intensive, involving the sifting of large volumes of imaging or spectroscopic data to find few candidates. We used early data from the Herschel Astrophysical Terahertz Large Area Survey to demonstrate that wide-area submillimeter surveys can simply and easily detect strong gravitational lensing events, with close to 100% efficiency.

When the light from a distant galaxy is deflected by a foreground mass—commonly a massive elliptical galaxy or galaxy cluster or group—its angular size and brightness are increased, and multiple images of the same source may form. This phenomenon is commonly known as gravitational lensing (1) and can be exploited in the study of high-redshift galaxy structures down to scales difficult (if not impossible) to probe with the largest telescopes at present (2–4) and to detect intrinsically faint objects. Surveys conducted at submillimeter wavelengths can be used to easily and efficiently select samples of strongly gravitationally lensed galaxies in wide-area submillimeter and millimeter surveys. The explanation for this lies in the steepness of

lengths that can particularly benefit from gravitational lensing because submillimeter telescopes have limited spatial resolution and consequently high source confusion, which makes it difficult to directly probe the populations responsible for the bulk of background submillimeter emission (5, 6). In addition, galaxies detected in blank-field submillimeter surveys generally suffer severe dust obscuration and are therefore challenging to detect and study at optical and near-infrared (NIR) wavelengths. By alleviating the photon starvation, gravitational lensing facilitates follow-up observations of galaxies obscured by dust and in particular the determination of their redshift (7). Previous submillimeter surveys for highly magnified background galaxies have predominantly targeted galaxy cluster fields (8). In fact, a blind search for submillimeter lensing events requires a large area because of their rarity and sub-arcseconds angular resolutions to reveal multiple images of the same background galaxies.

Although the first requirement has recently been fulfilled, thanks to the advent of the South Pole Telescope (SPT) (9) and the Herschel Space Observatory (Herschel) (10), the second is still the prerogative of ground-based interferometric facilities, such as the Submillimeter Array (SMA) and the IRAM Plateau de Bure Interferometer (PdBI), which because of their small instantaneous field of view are aimed at follow-up observations rather than large-area survey campaigns. Nevertheless, several authors (11–14) have suggested that a simple selection in flux density, rather than surveys for multiply imaged sources, can be used to efficiently and effectively select samples of strongly gravitationally lensed galaxies in wide-area submillimeter and millimeter surveys. The explanation for this lies in the steepness of
the number counts (the number of galaxies at a given brightness) of dust-obscured star-forming galaxies, which are usually referred to as submillimeter galaxies (SMGs) (15). Because of that, even a small number of highly magnified SMGs can substantially affect the shape of the bright end of the submillimeter source counts enhancing the number of SMGs seen at bright flux densities than would be expected on the basis of our knowledge of the unlensed SMG population (Fig. 1). Furthermore, the frequency of lensing events is relatively high in the submillimeter (17) because SMGs are typically at high redshift (z > 1) (16), and this increases the probability that a SMG is in alignment with, and therefore lensed by, a foreground galaxy. Other important contributors to the bright tail of the submillimeter counts are low-redshift (z ≤ 0.1) spiral and starburst galaxies (17) and higher redshift radio-bright Active Galactic Nuclei (AGNs) (18); however, both of these are easily identified, and therefore removed, in relatively shallow optical and radio surveys. Therefore, flux-density-limited submillimeter surveys could provide a sample of lens candidates from which contaminants can be readily removed, leaving a high fraction (close to 100%) of gravitational lens systems (Fig. 1). Because this selection of lens candidates relies on the properties of the background source (its flux density), it can probe a wide range of lens properties (such as redshifts and masses) and thus provide a valuable sample for studying the elliptical properties of lensing galaxies (19) as well as investigating the detailed properties of the lensed SMGs.

The submillimeter lens candidate selection at work. Although the approach presented above may be more efficient and vastly more time-effective than those exploited so far in the radio (20) or the optical (21, 22), at least seven times square degrees (deg²) of the sky must be observed in the submillimeter to produce a statistically significant sample of strongly lensed objects and a minimal contamination from unlensed galaxies. This is because the surface density of lensed submillimeter galaxies is predicted to be lower than ~0.5 deg⁻² for flux densities above 100 mJy at 500 μm (Fig. 1). Submillimeter surveys conducted before the advent of Herschel were either limited to small areas of the sky (15, 23) or were severely affected by source confusion due to poor spatial resolution (24). Therefore, no previous test of this selection method has been performed, although the SPT has recently mapped an area of more than 80 deg² at millimeter wavelengths (9) and found an “excess” of sources that could be accounted for by a population of gravitationally lensed objects.

The Herschel Astrophysical Terahertz Large Area Survey (H-ATLAS) (25) represents the largest-area submillimeter survey currently undertaken by Herschel. H-ATLAS uses the Spectral and Photometric Imaging Receiver (SPIRE) (26) and the Photodetector Array Camera and Spectrometer (PACS) (27, 28) instruments and, when completed, will cover ~550 deg² of the sky from 100 to 500 μm. H-ATLAS has been designed to observe areas of the sky with previously existing multiple-wavelength data: Galaxy Evolution Explorer (GALEX) ultraviolet (UV) data, Sloan Digital Sky Survey (SDSS) optical imaging and spectroscopy, NIR data from the UK Infrared Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS) Large Area Survey (LAS), spectra from the Galaxy And Mass Assembly (GAMA) (29) project, radio-imaging data from the Faint Images of the Radio Sky at Twenty-cm (FIRST) survey and the NRAO Very Large Array Sky Survey (NVSS). The first 14.4 deg² of the survey, centered on J2000 RA 09:05:30.0 DEC 00:30:00.0 and covering ~3% of the total area, was observed in November 2009 as part of the Herschel Science Demonstration Phase (SDP). The results were a catalog of ~6600 sources (30), with a significance >5σ, in at least one SPIRE waveband, where the noise (σ) includes both instrumental and source confusion noise and corresponds to ~7 to 9 mJy/beam.

The Herschel SPIRE 500-μm channel is favorable for selecting lens candidates because the submillimeter source counts steepen at longer wavelengths (24, 31). We used theoretical predictions (14) to calculate the optimal limiting flux density, above which it is straightforward to remove contaminants from the sample and maximize the number of strongly lensed high-redshift galaxies. The surface-density of unlensed SMGs is predicted to reach zero by S₅₀₀ > 100 mJy (14), and these objects are only detectable above this threshold if gravitationally lensed by a foreground galaxy (Fig. 1). The H-ATLAS SDP catalog contains 11 sources with 500 μm flux density above 100 mJy. Ancillary data in the field revealed that six of these objects are contaminants, four are spiral galaxies with spectroscopic redshifts in the range of 0.01 to 0.05 (see 32) for a detailed analysis of one of these sources, one is an extended galactic star-forming region, and one is a previously known radio-bright AGN (33). Although the number of these sources are few at

![Fig. 1. Selection of gravitational lenses at submillimeter wavelengths. The 500-μm source counts consist of three different populations (14): high-redshift SMGs; lower redshift late type (starburst plus normal spiral) galaxies; and radio sources powered by active galactic nuclei. Strongly lensed SMGs dominate over unlensed SMGs at very bright fluxes, where the count of unlensed SMGs falls off dramatically (yellow shaded region). The data points are from H-ATLAS (31).](image_url)
bright flux densities, the measured surface densities are consistent with expectations (Fig. 1) (17, 18). Exclusion of these contaminants left the five objects that form our sample of lens candidates (Table S1) (35), identified as ID9, ID11, ID17, ID81, and ID130.

**Unveiling the nature of the lens candidates.**

For gravitational lensing systems selected at submillimeter wavelengths, we would expect the lensing galaxy to be seen in optical and/or NIR images, in which the emission from the lens dominates over the higher redshift background SMG. In line with these expectations, all of the lens candidates have a close counterpart in SDSS or UKIDSS images (or both). A likelihood ratio analysis (34) showed that the probability of a random association between these bright submillimeter sources and the close optical/NIR counterparts is less than a few percent. Therefore, the optical and submillimeter emissions must be physically related, either because they occur within the same object or because of the effects of gravitational lensing, boosting the flux of the background source and indirectly affecting the likelihood ratio calculations. The redshift measurements support the latter scenario. Although the optical/NIR photometric/spectroscopic redshifts lie in the range of $z \sim 0.3$ to 0.9 (Table 1 and fig. S4) (35), the redshifts estimated from the submillimeter/millimeter spectral energy distributions (SEDs) (following the method described in (36, 37)) are distinctly different (Table 1). The lensed SMG photometric redshifts have been confirmed and made more precise through the spectroscopic detection, in these objects, of carbon monoxide (CO) rotational line emission, which are tracers of molecular gas associated to star-forming environments. Until recently, these kinds of detections were difficult to achieve without prior knowledge of the source redshift, which required extensive optical/NIR/radio follow-up observations. Because of the development of wide-bandwidth radio spectrometers capable of detecting CO lines over a wide range of redshifts, it is now possible for blind redshift measurements of SMGs to be taken without relying on optical or NIR spectroscopy (38, 39). ID81 was observed with the Z-Spec spectrometer (40, 41) on the California Institute of Technology Submillimeter Observatory. The data revealed several CO lines redshifted into the frequency range of 187 to 310 GHz; the strongest of these lines has been interpreted as the CO $J=7-6$ line, with an estimated redshift of $z = 3.04$ (42). This represents the first blind redshift determination by means of Z-Spec. We followed up this observation with the PdBI and detected CO $J=3-2$ and CO $J=5-4$ emission lines, redshifted to $z = 3.042$, confirming the Z-Spec-measured redshift (35). We also used the Zspec instrument (43, 44) on the NRAO Robert C. Byrd Green Bank Telescope (GBT) to obtain an independent confirmation of the redshift of ID81 (Table 1 and fig. S1) (35, 45) and to measure the redshift of ID130. We detected redshifted CO $J=1-0$ emission at $z = 2.625$ in the spectrum of ID130 (fig. S1) (35, 45). This redshift was confirmed by the PdBI with the observation of CO $J=3-2$ and CO $J=5-4$ lines, yielding a redshift of $z = 2.626$ (35). The Z-Spec spectrometer

---

**Table 2.** Derived parameters for the five lens candidates. Estimated mass in stars ($M_∗$) and Star Formation Rate (SFR) of the foreground galaxy derived from the best-fit to the UV/optical/NIR part of the SED; the Einstein radius measured from the SMA images ($\theta_E$); mass within the Einstein radius ($M_\text{E}$) estimated from the line-of-sight stellar velocity dispersion ($\sigma_\text{v}$) derived from the Faber-Jackson relation and the B-band luminosity produced by the best-fit to the UV/optical/NIR SED; Einstein radius ($\theta_\text{E}$) calculated from $\sigma_\text{v}$; infrared luminosity of the background source ($L_\text{IR}$), without correction for magnification, derived by fitting the submillimeter/millimeter part of the SED and the upper limits at optical and NIR wavelengths (Fig. 2); and visual extinction parameter ($A_V$) inferred for the background galaxy. All the quoted errors correspond to a 68% CI. For ID17, only the infrared luminosity and the extinction parameter of the background source are quoted because the lensing mass probably consists of two galaxies that can only be disentangled in the Keck images. The symbols $M_*$ and $L_*$ denote the total mass and the total luminosity of the Sun, respectively, and correspond to $M_*=1.99\times10^{30}$ kg and $L_*=3.839\times10^{33}$ erg s$^{-1}$. Dashes indicate lack of constraint.

<table>
<thead>
<tr>
<th>SDP ID</th>
<th>log($M_*$) ($M_\odot$)</th>
<th>log($M_{\text{E}}$) (yr$^{-1}$)</th>
<th>$\theta_E$ (arc sec)</th>
<th>log($M_\text{E}$) ($M_\odot$)</th>
<th>$\sigma_\text{v}$ (km sec$^{-1}$)</th>
<th>$\theta_\text{E}$ (arc sec)</th>
<th>log($L_\text{IR}$) ($L_\odot$)</th>
<th>$A_V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>10.79$\pm$0.16</td>
<td>$-$0.51$\pm$0.20</td>
<td>—</td>
<td>—</td>
<td>232.56$^{+75}_{-48}$</td>
<td>0.77$^{+0.49}_{-0.34}$</td>
<td>13.48$^{+2.2}_{-0.06}$</td>
<td>—</td>
</tr>
<tr>
<td>11</td>
<td>11.35$\pm$0.10</td>
<td>$-$0.08$\pm$0.18</td>
<td>—</td>
<td>—</td>
<td>258.62$^{+82}_{-62}$</td>
<td>0.91$^{+0.59}_{-0.40}$</td>
<td>13.61$^{+2.3}_{-0.06}$</td>
<td>—</td>
</tr>
<tr>
<td>17</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>13.57$^{+2.4}_{-0.06}$</td>
<td>—</td>
</tr>
<tr>
<td>81</td>
<td>11.17$\pm$0.08</td>
<td>$-$1.66$\pm$0.46</td>
<td>—</td>
<td>—</td>
<td>242.58$^{+77}_{-45}$</td>
<td>1.51$^{+0.98}_{-0.67}$</td>
<td>13.71$^{+2.4}_{-0.07}$</td>
<td>—</td>
</tr>
<tr>
<td>130</td>
<td>10.65$\pm$0.08</td>
<td>$-$1.17$\pm$0.39</td>
<td>—</td>
<td>—</td>
<td>174.42$^{+55}_{-39}$</td>
<td>0.81$^{+0.52}_{-0.36}$</td>
<td>13.45$^{+2.0}_{-0.08}$</td>
<td>—</td>
</tr>
</tbody>
</table>

---

**Fig. 2.** Spectra of the gravitational lens candidates. The UV, optical, and NIR data points (blue dots) are from GALEX, SDSS, and UKIDSS Las respectively. The submillimeter/millimeter data points (red dots) are from PACS/Herschel, SPIRE/Herschel, SMA, and Max-Planck Millimeter Bolometer (MAMBO)/IRAM. Upper limits at PACS/Herschel wavelengths are shown at 3$\sigma$. ID130 lies outside the region covered by PACS. The photometric data were fitted using SED models from (47). The background source, responsible for the submillimeter emission, is a heavily dust-obscured star-forming galaxy (red solid curve), whereas the lens galaxy, which is responsible for the UV/optical and NIR part of the spectrum, is characterized by passive stellar evolution.
observed the remaining three lens candidates (42) and detected CO lines at redshifts of \( z = 1.577 \) and \( z = 1.786 \) for ID9 (fig. S2) (35) and ID11, respectively, which are higher and inconsistent with the redshifts derived from the optical photometry/spectroscopy (Table 1). The Z-Spec CO measurements for ID17 are indicative of two redshifts; one, \( z = 0.942 \), that is in agreement with the optical redshift and a higher one, \( z = 2.31 \), which is indicative of a more distant galaxy.

To determine the morphological type of the foreground galaxies, we obtained high-resolution optical images for all five objects with the Keck telescope at \( g \)- and \( i \)-bands (35). ID9, ID11, ID81, and ID130 all have optical profiles that are consistent with elliptical galaxies (figs. S5 and S6 and table S4) (35). The interpretation of the results for ID17 is complicated by the presence of two partially superimposed galaxies in the optical images (fig. S7) (35), neither exhibiting the disturbed morphology expected for lensed objects. This indicates that ID17 may be a gravitational lens system with two foreground lensing masses at similar redshifts (\( z \sim 0.8 \) to 0.9)—possibly a merging system—with some molecular gas responsible for the CO emission detected by Z-Spec at \( z \sim 0.9 \) and confirmed with optical spectroscopy (Table 1). A fit to the UV/optical/NIR SEDs of ID9, ID11, ID81, and ID130 (46), using the models of (49), gives stellar masses in the range of \( 4 \times 10^{10} \) to \( 15 \times 10^{10} M_\odot \) (Table 2) and almost negligible present-day star formation, which is consistent with elliptical galaxies (Fig. 2).

For all five lens systems, the background source appears to be undetected in the Keck \( g \)- and \( i \)-band images, despite the flux magnification due to lensing. After subtracting the best-fit light profile from each lens (figs. S5 to S7) (36), we found no structure that could be associated with the background source in the residual images (figs. S5 and S6). We derived 3-\( \sigma \) upper limits from the residual maps (table S3) and corresponding NIR limits from the UKIDSS images. These upper limits were used to fit the SEDs of the background sources assuming the models of (47), calibrated to reproduce the UV-to-infrared SEDs of local, purely star-forming ultraluminous infrared galaxies (ULIRG) \( (10^{12} \leq L_\text{IR}/L_\odot < 10^{13}) \) (48). A visual extinction \( A_V > 2 \) is required to be consistent with the optical/NIR upper limits (Fig. 2 and Table 2), confirming severe dust obscuration in these galaxies along the line of sight. Our results indicate that these submillimeter bright gravitationally lensed galaxies would have been entirely missed by standard optical methods of selection.

We obtained observations at the SMA for ID81 and ID130 at 880 \( \mu \)m, with the aim of detecting the lensed morphology of the background galaxy (35). The SMA images reveal extended submillimeter emission distributed around the cores of the foreground elliptical galaxies, with multiple peaks (four main peaks in ID81 and two in ID130), which is consistent with a lensing interpretation of these structures (Fig. 3). The position of these peaks can be used to directly constrain the Einstein radius—the radius of the circular region on the sky (the Einstein ring) into which an extended source would be lensed if a foreground galaxy were exactly along the line of sight of the observer to the source (for a perfectly circular lens). The Einstein radius is a measure of the projected mass of the lens, so it can be used to derive the total (dark plus luminous) mass of the galaxy within the Einstein radius (Table 2) (35). Another measure of the total mass of a lens is the line-of-sight stellar velocity dispersion, \( \sigma_v \). We have estimated \( \sigma_v \) from the local Faber–Jackson (FJ) relation (50) between \( \sigma_v \) and the rest-frame B-band luminosity for elliptical galaxies. Assuming passive stellar evolution for the lens galaxies, which is appropriate for elliptical galaxies, we have extrapolated their rest-frame K-band luminosity to \( z = 0 \) [using the evolutionary tracks of (51)].

**Fig. 3.** Submillimeter and optical follow-up imaging of ID81 and ID130. The SMA images of ID81 and ID130 are shown in the top panels, centered on the optical counterpart, and were obtained by combining the visibility data from very extended, compact, and subcompact configuration observations. The Keck i-band image of ID81 and ID130 are shown in the bottom panels with the SMA contours superimposed (in red). The contours are in steps of \(-2\sigma, 2\sigma, 4\sigma, 6\sigma, 8\sigma, 10\sigma\ldots\), with \( \sigma = 0.6 \text{ mJy/beam} \). The SMA synthesized beam is shown in the bottom-left corner.

**Fig. 4.** Relationship between mass and luminosity for the lensing galaxy in ID81 and ID130. The rest-frame V-band luminosity was derived from the best-fit SED to the UV/optical/NIR photometric data; the mass within the Einstein radius is that measured directly from the SMA images. The light versus mass relation inferred for ID81 and ID130 (open circles) is consistent with that observed for the SLACS lenses [black dots, from (54), assuming an uncertainty of 0.025 dex in their mass estimates].
H-ATLAS SDP field are amplified by lensing in galax-
ies at high redshift. The fact that many (if not all) of the brighter
SMGs detected in the H-ATLAS SDP field are amplified by lensing
implies that unlensed \( z > 1 \) star-forming galaxies with flux
densities of more than 100 mJy at 500 \( \mu \)m are rare, with \( \lesssim 4 \) of them per 14.4 \( \text{deg}^{-2} \),
and 99% probability (assuming Poisson statistics). This
translates into a 0.32 \( \text{deg}^{-2} \) upper limit on the surface density of these sources. The
same limit should translate to the abundance of HLIRGs
with \( L_{IR} > 5 \times 10^{13} L_\odot \) at \( z < 4 \) because they
would also have 500–\( \mu \)m flux densities above 100 mJy, which has possible implications for the
role of feedback during the formation of the most
massive galaxies in the universe. By extrapolat-
ing our SDP findings to the full H-ATLAS field, we
determine a total sample of more than 100 bright-

glens sources, which with this we can further
improve this constraint.

References and Notes

1. When multiple images of the same background source
are formed, the event is known as strong gravitational


reason, we did not attempt any fit to the optical/NIR
source for H-ATLAS.


55. Herschel is an ESA space observatory with science

instruments provided by European-led principal

investigator consortia and with important participation

from NASA. U.S. participants in H-ATLAS acknowledge

support from NASA through a contract from JPL. This

work was supported by the Science and Technology

Facilities Council (grants PP/0024001 and

ST/G002533/1) and studentship SF/F005288/1. We

thank Agenzia Spaziale Italiana (ASI) for funding

through contract No. V016/070 CORS and ASI/Instituto

Nacional de Astrofísica (Mexico) grant 1072/2009 for the

Planck Low-Frequency Instrument (LFI) Activity of Phase

E2. Research supported in part by Consejo Nacional de

Ciencia y Tecnología (CONACyT), grant 39953-F

and 39548-F. The W. M. Keck Foundation is operated as a

scientific partnership among the California Institute of

Technology, the University of California, and NASA.

The Observatory was made possible by the generous

financial support of the W. M. Keck Foundation.
The Submillimeter Array is a joint project between the

Smithsonian Astrophysical Observatory and the Academia

Sinica Institute of Astronomy and Astrophysics and is

funded by the Smithsonian Institution and the Academia

Sinica. IRAM is supported by Institut National des

Sciences de l’Univers (INSU)/CNRS (France), Max Planck

Society (MPG) (Germany), and Instituto Geográfico

Nacional (IGN) (Spain). Z-spec was supported by NSF

grant AST-0808990 to J.A. and by the CEC NSF

Cooperative Agreement AST-0838261. Support was

provided to J.K. by an NSF Graduate Research Fellowship.

Z-spec was constructed under NASA SARA grants

NAGS-11911 and NAGS-12788 and an NSF Career

grant (AST-0239270) and a Research Corporation

Award (RO10828) to J.G. in collaboration with JPL,

California Institute of Technology, under a contract

with NASA. Construction of and observations with the Z-spectrometer have been supported by NSF grants

AST-0503946 and AST-0708653. NRAO is a facility of the NSF operated under
cooperae agreement by Associated Universities. The optical spectroscope redshift of ID130 was derived
from observations obtained with the Apache Point

Observatory 3.5-m telescope, which is owned and

operated by the Astrophysical Research Consortium.

The optical spectroscopic redshifts of ID9 and ID1 used

with the William Herschel Telescope, which is

operated on the island of La Palma by the Isaac Newton

Group in the Spanish Observatorio del Roque de los

Muchachos of the Instituto de Astrofísica de Canarias.

For the use of Keck, SMA, and CSO, the authors wish
to recognize and acknowledge the very important cultural

role and reverence that the summit of Mauna Kea has

always had within the indigenous Hawaiian community.

We are most fortunate to have the opportunity to conduct

observations from this mountain.

Supporting Online Material

www.sciencemag.org/cgi/content/full/330/6005/800/DC1

SOM Text

Figs. S1 to S9

Tables S1 to S4

References

SOM Fig. 1

8 June 2010; accepted 21 September 2010

10.1126/science.1193420