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Astronomical Science with Adaptive Optics at the W. M. Keck Observatory

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ABSTRACT. The first refereed science papers based on data with the Keck II natural guide star (NGS) and laser guide star (LGS) adaptive optics (AO) system were published in 2000 January and 2005 May, respectively. As of the end of 2012 a total of 260 refereed science papers have been published based on Keck NGS AO data and 152 with the Keck LGS AO system. This paper provides an overview of the first dozen years of scientific productivity with Keck AO and the lessons that can be drawn from this experience. The performance and limitations of the existing Keck AO systems are also discussed along with the technical developments currently underway to improve the scientific reach of these systems. The Keck AO capabilities are in high demand by a broad science community, a community that has expanded as new capabilities, especially LGS AO, have been added.

Online material: color figures

1. INTRODUCTION

The first implementation of AO on a large (8–10 m) telescope was made on the Keck II telescope (Wizinowich et al. 2000) and produced a greater than 10 fold improvement in angular resolution beyond seeing-limited observations. While this early implementation relied on a bright NGS (R-magnitude <15) to measure the atmospheric turbulence, and therefore was limited to only a small fraction of the sky, it has produced many spectacular results including the first image of a planetary system (Marois et al. 2008) beyond our own (see also Fig. 1), and the detection of carbon monoxide and water in the atmosphere of one of these planets using integral field spectroscopy behind Keck NGS AO (Konopacky et al. 2013).

The first implementation of LGS AO on a large telescope was also made on the Keck II telescope (Wizinowich et al. 2006; van Dam et al. 2006). LGS AO provided the W. M. Keck Observatory (WMKO) science community the ability to achieve high angular resolution observations over a sizable fraction of the sky (e.g., the sky coverage at a galactic latitude of 70 is 70% for a Strehl ratio >0.1 and 30% for a Strehl ratio >0.2; see Johansson et al. 2008) and has enabled a wide range of science that was previously not feasible from ground-based and/or space-based observatories (Keck II's LGS AO resolution in the near-infrared exceeds that of HST by a factor of 4, the ratio of the two telescopes' diameters). High impact science resulting from the Keck LGS AO system has included observations of Kuiper Belt Objects that led to the designation of Pluto as a minor planet (e.g., Brown and Schaller 2007), precision characterization of the supermassive black hole at the center of our own Galaxy (e.g., Ghez et al. 2008; Meyer et al. 2012), the study of the interiors of young galaxies (e.g., Stark et al. 2008), and the detection of low-mass dark satellite galaxies confirming a Universe composed of cold dark matter (e.g., Vegetti et al. 2012).

An identical NGS AO system was implemented on the Keck I telescope in 2001 to support observations with the Keck Interferometer. The real-time wavefront controllers and wavefront sensor cameras on both the Keck I and II systems were upgraded in 2007 (Johansson et al. 2008). The Keck I system has been upgraded to a LGS AO system and science observations began in 2012 May (Chin et al. 2012). The upgrade includes a laser (Sawruk et al. 2010), a beam transport system, a laser launch telescope, additions to the AO system, and the movement of the existing OSIRIS science instrument to Keck I. Figure 2 shows the two Keck LGS AO systems observing the Galactic Center.

The science productivity of the Keck AO facilities from 2000 through 2012 is presented in § 2. This is followed by a brief overview of the science performance in § 3. The development activities currently underway at WMKO to further improve the scientific productivity of the Keck AO facilities are summarized in § 4. Some lessons learned are discussed in § 5 before concluding.

2. SCIENCE PRODUCTIVITY

Figures 3 and 4 plot the number of refereed science papers published each year based on Keck NGS and LGS AO data, respectively. These plots group the science papers into three broad categories: solar system, galactic, and extra-galactic science. The exoplanet portion of galactic science, a growing application for Keck NGS AO in recent years, is shown separately in Figure 3. The type of science has changed with the advent of

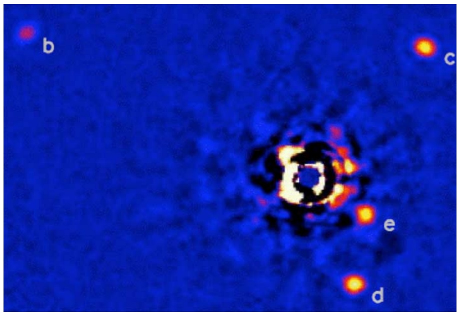

FIG. 1.—First four planet image of HR 8799, obtained with Keck II NGS AO in L'-band (Marois et al. 2010). See the electronic edition of the *PASP* for a color version of this figure.

LGS AO as shown in Table 1. NGS AO is sufficient for the study of many solar system and galactic objects whereas LGS AO has opened up the extragalactic field and allowed new, fainter galactic objects to be observed.

A more detailed breakdown of the types of science being performed with the LGS AO system is provided in Table 2.

A note on determining the number of refereed papers: The refereed Keck AO papers were primarily identified by searches of http://arXiv.org and the NASA ADS abstract service using keywords such as Keck combined with adaptive optics, NIRC2, OSIRIS, interferometer, or laser. Additional papers were found by similar searches of journal databases and cross-referencing with the Keck publication database. Each paper that used data from the Keck AO systems was counted as one paper in Figures 3 and 4 even if it also used data from other non-AO Keck instruments or other observatories; the few papers that contained both Keck NGS and LGS data were counted as LGS. When comparing to other Keck instruments or other LGS AO systems a paper that used data from multiple systems is divided between the systems as equal fractions.

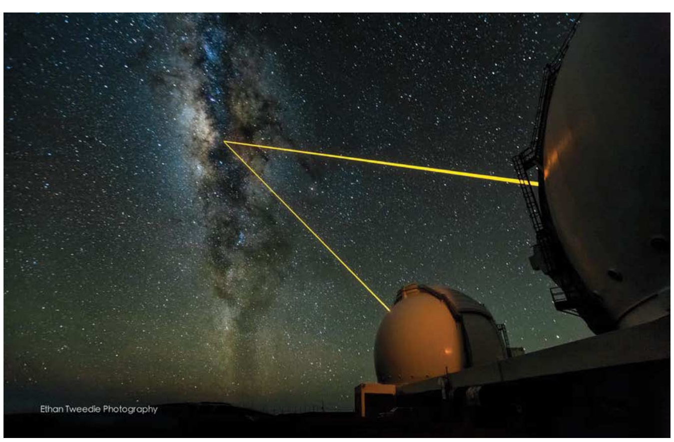

FIG. 2.—The Keck I and II LGS AO systems being used to observe the center of our galaxy (photo credit: Ethan Tweedie photography). See the electronic edition of the *PASP* for a color version of this figure.

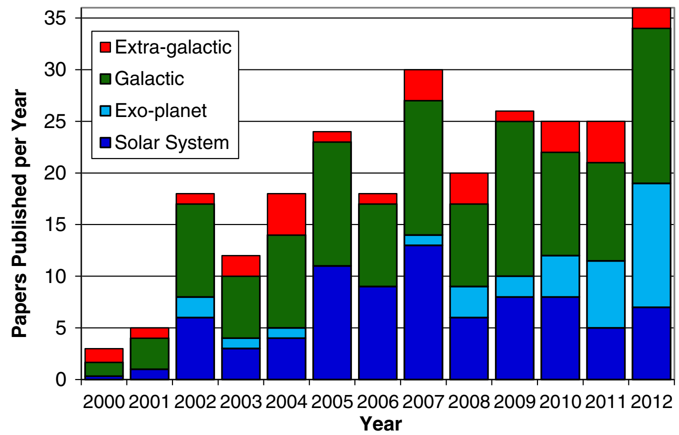

FIG. 3.—Refereed Keck II NGS AO science papers published each year. See the electronic edition of the *PASP* for a color version of this figure.

A brief summary of the science instruments that have been used with Keck AO is provided in Table 3. KCAM (Keck CAMera) was the engineering camera (provided by James Larkin) used for the first science with Keck II NGS AO. NIRSPEC (Near InfraRed SPECtrograph; McLean et al. 1998) was designed for seeing-limited observations but was pressed into service with AO by implementing some reflective reimaging optics between the AO system and NIRSPEC that provide a factor of 10 in magnification; SCAM is the slit viewing imager in the NIRSPEC instrument. NIRC2 (Near-InfraRed Camera 2; PI: Keith Matthews) is the imaging camera built for operation with the AO system which also provides grism, coronagraphic, and aperture masking options. The interferometer (IF) that combines the light from the two Keck telescopes requires AO systems on both telescopes. The interferometer modes that have produced science through 2012 include V^2 (Visibility squared; Colavita et al. 2003), nuller (Colavita et al. 2009), and

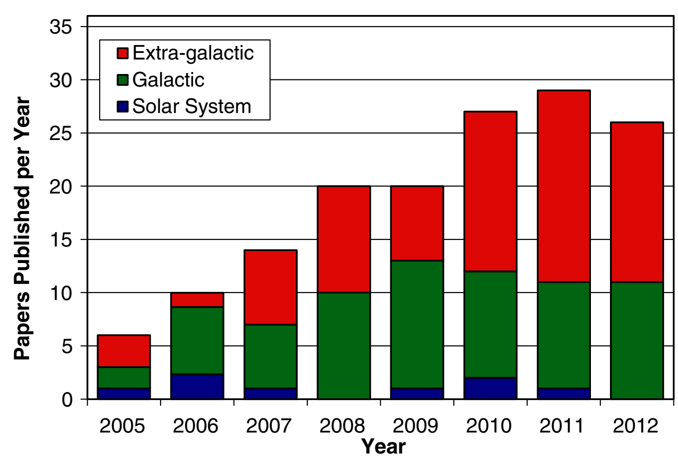

FIG. 4.—Refereed Keck II LGS AO science papers published each year. See the electronic edition of the *PASP* for a color version of this figure.

TABLE 1

Refereed Keck II AO Science Papers by Mode and Science Category Through 2012

Type	NGS (%)	LGS (%)
Solar system …………	33	7
Galactic ………………	56	44
Extragalactic …………	11	49

self-phase referencing (i.e., using part of a target's light for fringe tracking and part for a science measurement; Woillez et al. 2012). The AO science instrument OSIRIS (OH-Suppression InfraRed Integral field Spectrograph; Larkin et al. 2006) is primarily used for integral field spectroscopy but also includes a separate imaging camera in the same dewar. The NIRC2, OSIRIS and NIRSPEC science instruments are used with both NGS and LGS AO modes. The published interferometer science was obtained with NGS AO; interferometer science observations were performed with LGS AO on both telescopes in 2012 July.

The refereed AO science papers by instrument and year are shown in Figure 5. NIRC2 has been the most productive Keck AO instrument with 274 of the papers, representing 67% of the total.

Figure 6 is a plot of the percentage of Keck II science nights assigned to AO science observations by the time allocation committees (TACs). Since 2006 approximately 45% of the Keck II science time has been used with AO; of these nights 67% are LGS nights. The spike in nuller allocation in 2008 was due to a NASA key science program to measure dust around nearby stars

TABLE 2

Refereed Keck II LGS AO Papers by Type of Science Through 2012

Area	Sub-topic	Number of papers
	Brown dwarfs and low mass stars	39
	Galactic center	17
	Compact objects	3
	Disks	3
	Magnestar	1
Galactic ……….	Nova	1
	High redshift galaxies	25
	Gravitational lensing	17
	AGN and black holes	12
	Supernovae	10
	Stellar populations	7
	Gamma ray burst	1
Extra-galactic …..	Optical transient	3
	Interstellar medium	1
	Kuiper belt	4
Solar system …..	Planets	2
	Asteroids	2

(Millan-Gabet et al. 2011). The V^2 nights include nights used for self-phase referencing observations.

It is difficult to compare science productivity between instruments. One potentially illustrative comparison, with plenty of caveats, is provided in Figure 7 which compares the TAC-allocated science time and refereed science papers by instrument for a single year. The optical instruments had 60% of the science time in 2009 and produced 72% of the 2010 papers in this comparison (the papers used to produce this figure were the Keck publication database). The seeing-limited near-IR instruments had 16% of the science time and produced 9% of the science papers. The AO science instruments had 25% of the science time and produced 18% of the papers. NIRC2 was the most productive AO, and near-IR, instrument with 11% of the 2009 science nights and 12% of the 2010 papers. The interferometer's productivity was also good with 4% of the 2009 science nights (2 nights are counted for each interferometer night since both telescopes are required) and 3% of the 2010 science papers. OSIRIS is a newer instrument and its paper count has been relatively low so far for a number of reasons, including the initial challenge of the associated data reduction and its heavy use for observations of extragalactic targets requiring long integrations. To improve the sensitivity of OSIRIS a higher throughput grating was installed in late 2012 (Adkins et al. 2012).

Table 4 lists the Keck AO-based papers published in 2010 and 2011 by journal and type of science. The majority of these Keck AO-based papers (59%) were published in the Astrophysical Journal (including ApJL and ApJS).

Keck AO data is frequently used in conjunction with other data. In 2010 and 2011, 63% of the refereed papers that used Keck AO data also included data from other telescopes or Keck instruments. In 2012, this percentage increased to 73% largely due to the increased use of NIRC2 imaging of exoplanet systems in conjunction with other observations (nine in 2012 versus two in 2011).

The observing time at WMKO is divided between Caltech, UC, NASA and UH as 35%, 35%, 16.5% and 12.5% shares, respectively; in addition, the National Science Foundation's Telescope System Instrumentation Program made available 128 WMKO nights between 2006 and 2011 through the National Optical Astronomy Observatory. One measure of AO's impact on the broad science community is the number of authors on papers that used data from the WMKO AO systems. This analysis, performed for the 62 refereed papers published in 2012 using Keck AO data, is shown in Table 5. The number of authors is distributed into five institutional categories: Caltech, University of California (UC), University of Hawaii (UH), other U.S. institutions, and non-U.S. institutions. The second and third rows show the numbers for the lead authors. The last two rows show the numbers for all of the authors on each paper including the lead authors. Summing up all of the author names gives a total of 822 names. Since some authors appear on more than one

TABLE 3

SOME DETAILS OF THE SCIENCE INSTRUMENTS USED WITH KECK II AO (THE LISTED INSTITUTION(S) IS THE DEVELOPER OF THE INSTRUMENT)

Name (institution)	Date of first AO light	Detector (# pixels and type)	Plate scale (arcsec/pixel)	Spectral resolution	Notes
KCAM (UCLA)	Feb., 1999	256 × 256 NICMOS3 (HgCdTe)	0.017	n/a	Removed in 2001
NIRSPEC includes SCAM	Feb., 2000 for spectra	1024 × 1024 InSb Aladdin-3	0.0185 low R 0.013 high R	Low = 2000 High = 25000	Designed for non-AO. Used without & with AO
imager (UCLA)	Apr., 2000 for imaging	256 × 256 PICNIC for slit viewing	0.017	n/a	
NIRC2 (Caltech)	Aug., 2001	1024 × 1024 InSb Aladdin-3	0.01 and 0.04	~5000 with grisms	
V2 (JPL, WMKO, NExScI)	Mar., 2001	Hawaii-2	0.005	up to 1700	Visibility at H, K & L
Nuller (JPL, WMKO, NExScI)	Aug., 2004	DRS HF-128 BIB	0.025		Nulling at N
			0.02 for imager	n/a	
OSIRIS (UCLA)	Feb., 2005	2048 × 2048 Hawaii-2 (HgCdTe)	0.02, 0.035, 0.05 to 0.10	3800 (3000 for 0.1″/pix)	Integral field spectrometer

paper the number of unique authors was determined to be 609. The average number of authors on a 2012 paper was 13.3.

Another measure of AO's impact is its usage by students. A total of 43 PhD dissertations published in 2009 and 2010 used data collected at Keck Observatory; 42% of these dissertations made use of Keck AO data and 49% of these students were co-authors on papers using Keck AO data.

Keck AO's productivity with respect to other AO facilities is illustrated in Figure 8 and Table 6. Figure 8 shows all of the LGS AO refereed science papers published worldwide through 2012 by year and Observatory. The Keck LGS system has produced 72% of all LGS papers from 2004 to 2012. The telescopes shown in Figure 8 include the Air Force Starfire Optical Range 1.5 m, the Calar Alto 3.5 m, the Keck II 10 m, the Lick 3 m, the Gemini-North 8 m, the European Southern Observatory Very Large Telescope (VLT) 8 m, the Palomar 6 m, the Subaru 8 m and the Palomar Robo-AO 1.5 m. See Wizinowich (2012b) for a comparison of these LGS AO systems.

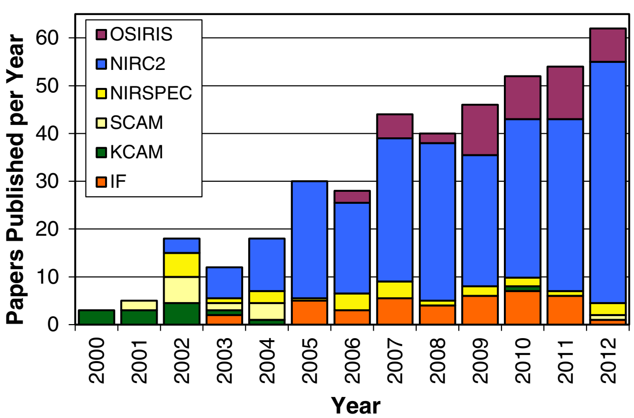

FIG. 5.—Keck II AO refereed science papers published each year by science instrument. See the electronic edition of the *PASP* for a color version of this figure.

The refereed AO-based science papers published in the Astrophysical Journal in 2010 are listed by AO system and type of science in Table 6. In the case where more than one AO system is used for a paper the paper is evenly distributed among the AO systems. Although the Astrophysical Journal is only one of several journals used to publish astronomical science, the high fraction of AO papers in this prestigious journal which involve Keck (45%) testifies to the high impact of the Keck II AO system. Since European astronomers likely favor Astronomy & Astrophysics (A&A) a search was made of VLT AO papers in A&A in 2010: 13.83 papers were published based on NACO data and 3.5 based on SINFONI AO data (compared to 2.83 for WMKO).

Science with AO has come a long way over the past decade and AO at Keck has played a significant role in this high angular resolution revolution. Keck AO has enabled a wide range of astronomical science over this time and it has been adopted, and is in demand, by a large segment of our user community. Scientific productivity is good in the context of the other Keck science

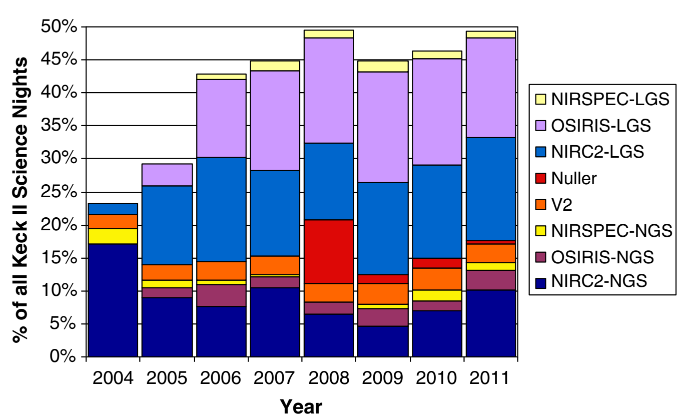

FIG. 6.—Percentage of Keck II nights allocated to AO science by instrument and year. See the electronic edition of the *PASP* for a color version of this figure.

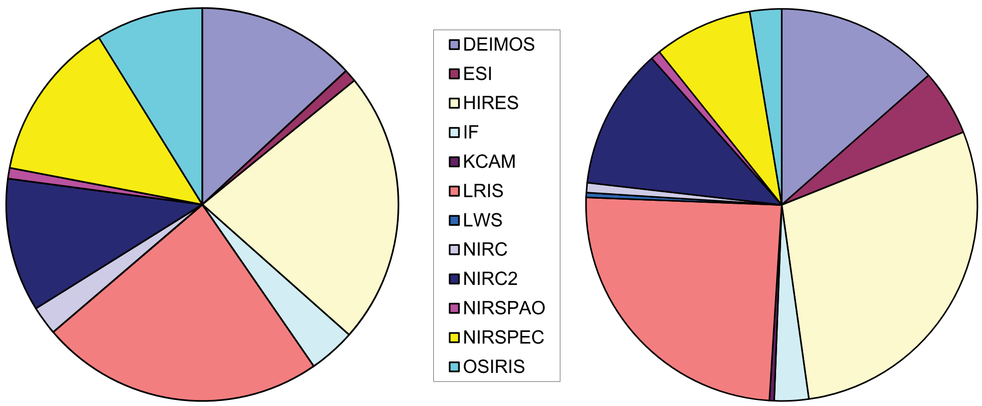

FIG. 7.—TAC-allocated science nights in 2009 (*left*) and refereed science papers in 2010 (*right*) by Keck science instrument. The AO instruments are IF (Interferometer), KCAM, NIRC2, NIRSPAO (NIRSPEC behind AO), and OSIRIS. See the electronic edition of the *PASP* for a color version of this figure.

instruments. Keck AO is doing well, and Keck LGS AO is doing very well, with respect to AO systems on the other large telescopes.

3. SCIENCE PERFORMANCE

The current Keck II AO performance is illustrated in Figure 9 with a plot of K-band Strehl ratio (SR) versus the R-band magnitude of the on-axis tip-tilt star (this is the effective R-magnitude measured by the wavefront sensor in NGS mode and by the tip-tilt sensor in LGS mode). NGS AO corrected star images from the NIRC2 science camera are shown for reference.

Figure 9 is an incomplete indicator of what to expect on a particular science program. We will therefore now look at the quantitative performance for two specific science cases. The first of these science cases is a survey of field brown dwarfs performed by Liu (2008) between 2005 and 2007. Liu's plots of K-band Strehl and full-width-half-maximum (FWHM) are reproduced in Figure 10. Tip-tilt stars as faint as $R \sim 18$ mag and as a much as 60″ off-axis were used in this survey (see also Liu 2006). This survey was performed to find low mass binaries in order to use their measured orbits to determine the component masses.

From Kepler's third law, the error in the binary mass determination, dM/M scales as 3dθ/θ, the positional errors in the measured orbit. The relative positional, and photometric, errors are found to scale with the measured FWHM and Strehl ratio for the observation, as seen in the case of the 2MASS 1534-2952AB low mass binary (Liu et al. 2008) and 2MASS 2206-2047AB (Dupuy et al. 2009) plotted in Figure 11. The largest terms in the error budget for this science case are bandwidth and measurement errors due to both tip-tilt and higher order correction; these are the errors being addressed by a number of the AO development activities discussed in § 4.

A second science case considered here is the Galactic Center. The Keck II LGS AO system has been used to measure the properties of stars around the supermassive black hole at the center of our galaxy (Ghez et al. 2005; Do et al. 2013). The orbital

TABLE 4
KECK AO PAPERS PUBLISHED IN 2010 AND 2011 BY JOURNAL AND TYPE

	Solar system		Galactic			Extragalactic			
Journal	LGS	NGS	IF	LGS	NGS	IF	LGS	NGS	2010/11 Total
A&A		2	1		2	2	1	2	10
AJ				3	2		5		10
ApJ			8	14	13	1	12.5	0.5	49
ApJL		1			2		7	2	12
ApJS				1					1
Icarus	3	10							13
MNRAS					1		5		6
Nature					1		2		3
PASP					1				1
2010/11 Total	3	13	9	18	22	3	32.5	4.5	105

The paper counts are organized by type of science and AO mode.

TABLE 5
NUMBER OF AUTHORS AND THEIR INSTITUTIONS FOR PAPERS PUBLISHED IN 2012 BASED ON KECK AO OBSERVATIONS

	Caltech	UC	UH	Other-US	International	Total
Lead authors	10	13	10	24	5	62
Unique lead authors	9	13	8	21	5	56
All authors	110	144	40	296	232	822
Unique all authors	68	93	22	240	186	609

measurements of these stars are currently limited to 0.17 mas in positional error and 17 km/s in radial velocities (Ghez et al. 2008). The accuracy of these measurements is limited by source confusion in this very crowded stellar region. Source confusion could be significantly reduced with improved knowledge of the AO-corrected point spread function (PSF); this is the goal of some of the AO development work discussed in § 4.

Another category of science performance is observing efficiency. Observing with AO includes some additional overheads not encountered during seeing-limited observations. This is illustrated with the plot of observing efficiency for the Keck II LGS AO system shown in Figure 12. The weather loss is higher than for non-LGS AO nights because Keck LGS AO cannot be used in the presence of more than one magnitude of extinction from cirrus; the actual weather loss is less than the 23% shown since observers will switch to NGS AO or NIRSPEC programs. There is additional overhead due to laser system checkout at the start of the night (~30 minutes), and the time required to close the AO loops (1–2 minutes) after a telescope slew and after moving the science object on the science detector (a few seconds). There are also faults due to both the AO system and laser system. The need to prevent illuminating satellites by participating in the U.S. Space Command's Laser Clearing House (LCH; more than half of the LCH lost time was in 2011), to prevent illuminating aircraft via the use of spotters, and to not impact observations by other telescopes on Mauna Kea via use of the laser traffic control system, results in considerable additional operational complexity but overall only small losses in observing time. The observing efficiency for the Keck II LGS AO system continues to improve, from an average of 29% for the 2005 to 2007 period to 45% in 2012. The total open shutter science time is 2667 hr through 2012.

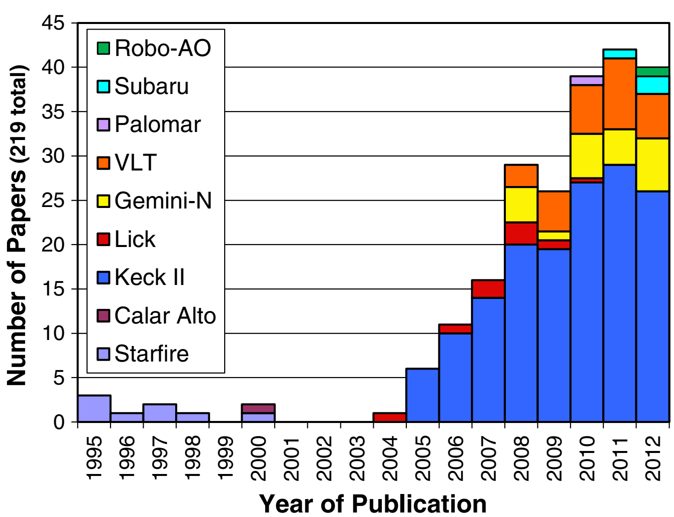

FIG. 8.—Number of refereed astronomical science papers published each year using data from all LGS AO systems world-wide. See the electronic edition of the *PASP* for a color version of this figure..

4. ADAPTIVE OPTICS DEVELOPMENTS

The Observatory, as part of its strategic vision, is continuing its efforts to provide improved AO capabilities to support the cutting edge high angular resolution science being done by the Keck user community.

The performance of the existing Keck LGS AO systems is limited by measurement and bandwidth errors on the LGS for the case of a bright tip-tilt star, and by measurement and bandwidth errors on the tip-tilt star for the case of a faint tip-tilt star (see for example the error budget in Johansson et al. 2008). In addition quantitative astrometry, photometry, morphology and kinematics are often limited by insufficient knowledge of the PSF. The current Keck AO development efforts are intended to address these limitations.

Improvements that should start bearing scientific fruit over the next few years include improved Keck II LGS AO performance with projection of the laser from behind the telescope's secondary mirror and the implementation of a new laser, improved tip-tilt performance with a near-infrared tip-tilt sensor for the Keck I LGS AO system, and PSF estimates provided with all AO science observations. In the longer term, the Observatory plans to implement a Next Generation AO (NGAO) facility.

Keck II LGS AO center launch: The Keck II LGS AO system has so far used a laser launch telescope mounted to the side of the Keck telescope. The side launch of the laser results in perspective elongation of the LGS as seen by the AO wavefront sensor, due to the thickness of the sodium layer. The NSF Major Research Instrumentation (MRI) program has provided funding to implement a center launch telescope. The center launch system is planned to be installed on the Keck II telescope in 2013 (Wizinowich & Chin 2013).

TABLE 6

Astrophysical Journal (ApJ and ApJL) Papers Published in 2010 Based on AO Observations

	Solar system		Galactic			Extragalactic			
System	LGS	NGS	IF	LGS	NGS	IF	LGS	NGS	ApJ 2010 Total
Keck II AO	0	1	5	6.0	6.5	1	9	1	29.5
Gemini ALTAIR	0	0	0	1.5	2.5	0	1	2	7.0
Gemini NICI	0	0	0	0.0	1.3	0	0	1	2.3
Subaru AO188	0	0	0	0.0	1.0	0	0	1	2.0
VLT NACO	0	0	0	0.3	4.6	0	0	2	6.8
VLT MAD	0	0	0	0.0	2.0	0	0	0	2.0
VLT SINFONI	0	0	0	0.8	1.3	0	0	1	3.0
VLT CRIRES	0	0	0	0.0	1.0	0	0	0	1.0
VLT MACAO	0	0	1	0.0	0.0	0	0	0	1.0
AEOS LYOT	0	0	0	0.0	1.5	0	0	0	1.5
CFHT PUEO	0	0	0	0.0	1.0	0	0	0	1.0
MMT AO	0	0	0	0.0	3.3	0	0	0	3.3
Palomar PALAO	0	0	0	1.0	4.5	0	0	0	5.5
ApJ 2010 Total	0	1	6	10	30	1	10	8	66

The paper counts are organized by type of science, AO mode and AO system.

New Keck II laser: The current, ~15 year old, dye laser will be replaced with a 20 W Raman fiber amplified laser fabricated by a consortium of TOPTICA and MPBC (Friedenauer et al. 2012), thanks to funding from the Gordon and Betty Moore Foundation and the W. M. Keck Foundation. This laser was developed as part of an effort led by the European Southern Observatory with collaboration from WMKO, TMT, AURA and GMT (the U.S. collaboration was made possible by some NSF funding). The new laser is expected to have at least 10 times the coupling efficiency to the sodium layer thanks to its continuous wavelength and the use of some of the laser power to re-pump the sodium atoms. The laser will be implemented on the elevation ring of the telescope in 2015 and will be projected with the center launch telescope discussed above.

Keck I near-infrared tip-tilt sensor: A near-IR tip-tilt sensor, based on a Hawaii-2RG detector, is being developed for implementation with the Keck I LGS AO system in 2013 with funding by the NSF Advanced Technologies and Instrumentation (ATI)

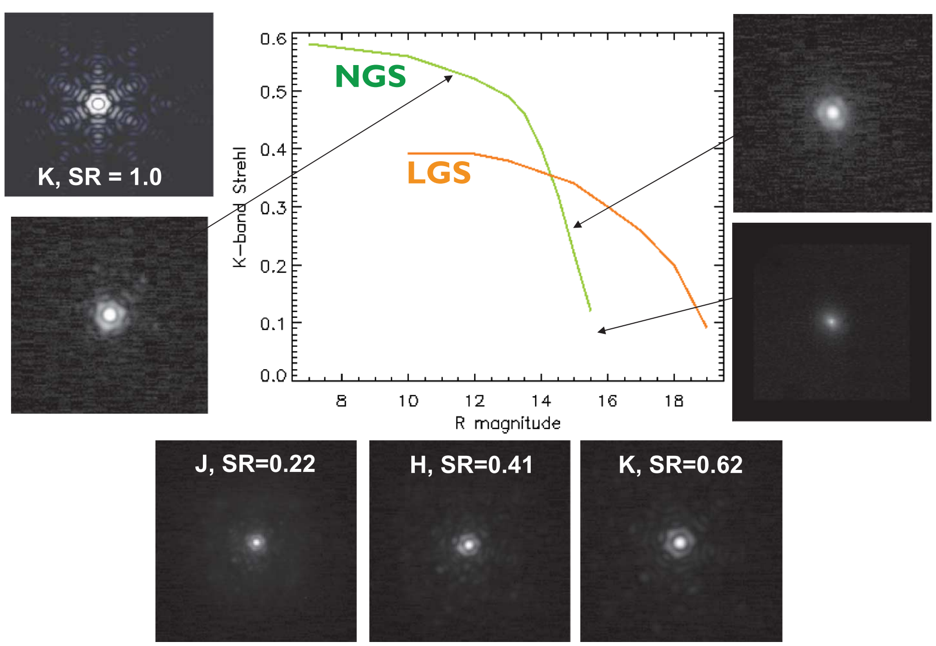

Fig. 9.—(*Top*) Keck II AO K-band performance versus R-magnitude of the on-axis NGS (as measured by relative counts on the wavefront sensor) under average conditions, as illustrated by a plot of Strehl ratio and NIRC2 images of the NGS. The top-left image is the theoretical perfect point spread function for the Keck telescope. (*Bottom*) NIRC2 images of the same NGS at J, H and K-band. Adapted from van Dam et al. (2007). See the electronic edition of the *PASP* for a color version of this figure.

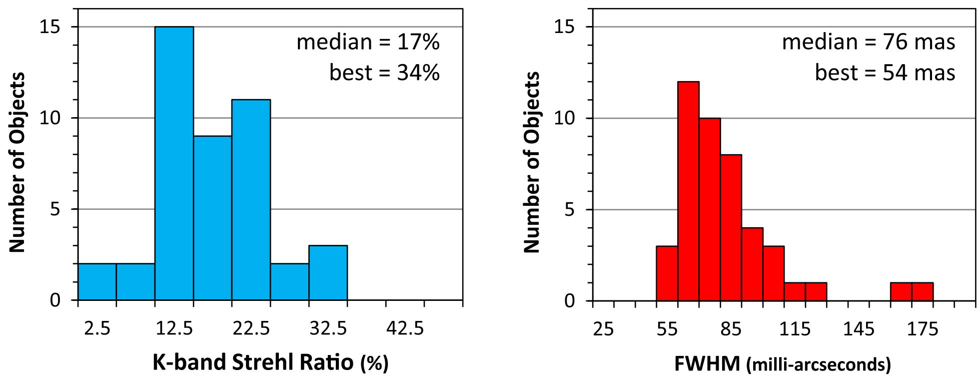

FIG. 10.—K-band Strehl ratio (*left*) and FWHM (*right*) from a Keck II LGS AO survey of field brown dwarfs by Liu (2008). No data was discarded. The data includes a mix of seeing conditions and off-axis tip-tilt star properties. See the electronic edition of the *PASP* for a color version of this figure.

program (Wizinowich 2012a). Tip-tilt sensing will be done on the AO-corrected core of NGS. Dichroic beamsplitters will be used to send the Ks-band or H-band light, over a 100″ square field, to the sensor. When using Ks-band light the sky fraction over which the one-dimensional rms tip-tilt error is less than 20 mas will be increased from 45% to 75%.

Point spread function determination: Two efforts toward PSF estimation for Keck AO-corrected observations are currently underway. One for reconstructing the NGS AO PSF based on wavefront sensor telemetry (Jolissaint et al. 2012b) and phase diversity measurements (Jolissaint et al. 2012a), and a second to estimate the PSF as a function of field position based on atmospheric profiler data (Fitzgerald et al. 2012). The work by Jolissaint et al., so far demonstrated on a bright on-axis NGS, will be extended to faint NGS and LGS PSF determination with NSF ATI funding beginning in late 2012. The determination of the off-axis PSF is a project led by A. Ghez at UCLA in collaboration with the Optical Sciences Company and WMKO with funding from the W. M. Keck Foundation.

Next generation adaptive optics: WMKO's NGAO facility (Wizinowich et al. 2010) completed its preliminary design in 2010 with funding from the NSF Telescope Systems and Instrumentation Program (TSIP). Further development of this project is on hold pending the identification of sufficient funding. The development activities, described above, are all components of, or risk reduction for, the NGAO project. The NGAO system would provide significantly higher Strehl ratios, greater than 80% at K-band, due to the use of multiple lasers to reduce focal anisoplanatism, and nearly complete sky coverage due to the use of LGS AO corrected tip-tilt stars in the near-infrared.

5. LESSONS LEARNED

Davies and Kasper (2012) identified a number of lessons learned from AO that are also largely valid for the Keck systems. These lessons are listed (in italics) in the following list along with some discussion from the WMKO perspective which may shed some light on reasons behind the productivity of the Keck AO systems:

1. *There is a vast gulf between demonstrating a technology and making it scientifically productive*. The original Keck AO systems, and the upgrades to these systems, have been strongly driven by the science requirements and the need to produce operational facilities. The Keck science community has been very engaged through AO science teams that have worked with the AO developers to understand what was desirable scientifically and what was practically achievable. Careful attention has been paid to the details of how these systems are used with the science instruments and telescope to perform science observations. Technology demonstrations are more cost-effectively performed on smaller telescopes and a technology demonstration is not fully complete until it has been used to produce astronomical science papers. It is only when the options are very limited, such as with LGS AO, that WMKO has taken the risk of first demonstrating these technologies scientifically on a Keck telescope.

2. *AO ought to be accessible to targets for which the primary selection criteria are astrophysical rather than technical*. NGS AO has the serious technical limitation of only allowing science near relatively bright NGS. How big a limitation this was is revealed by the dramatic increase in extragalactic science that has been made possible with the much higher sky coverage offered by Keck LGS AO. This point also argues for continuing to increase the sky coverage, and the performance versus sky coverage, by improving the tip-tilt sensing (the rationale behind the development of a near-infrared tip-tilt sensor). The current Keck AO systems have seven reflections and one dichroic in the path to the science instrument; the resultant ~30% throughput loss and higher thermal background increases the integration time and reduces accessibility for faint extra-galactic targets.

3. *A simple set of AO performance metrics ought to be widely applicable to all types of astrophysical targets and science cases.* Ultimately, astronomers are interested in being able to make quantitative statements about astrophysical quantities such as mass, age, distance, composition, kinematics, morphology, etc.

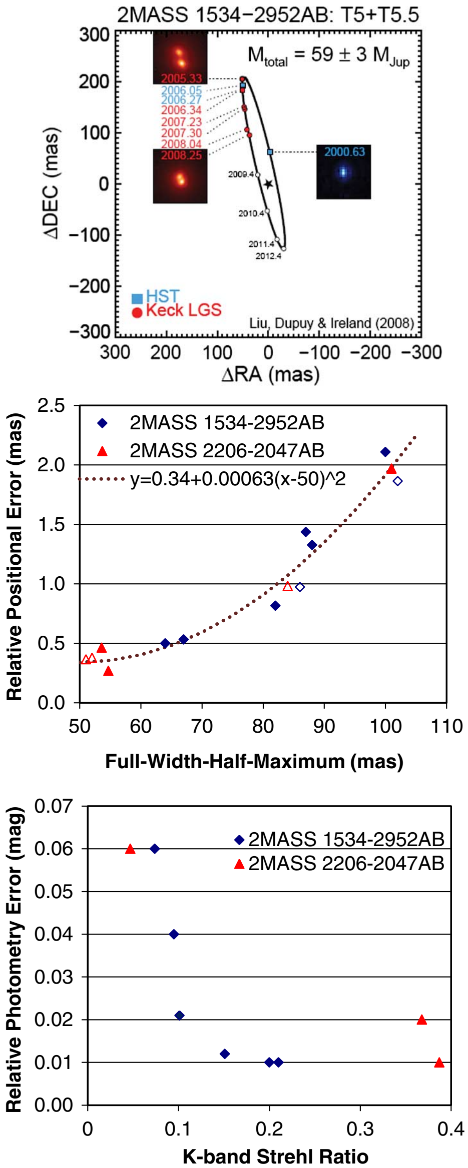

FIG. 11.—(*Top*) Orbit of 2MASS 1534-2952B about component A as determined by Keck II LGS AO and HST observations (Liu et al. 2008); the Keck observations were performed at air masses of 1.55 to 2.05, using a $R = 16.2$ magnitude guide star at a separation of 31″ from the science target. (*Middle*) Relative positional errors (square root of the sum of the squares of the separation and position angle errors) as a function of full-width-at-half maximum for the Keck II LGS AO observations of this low mass binary and 2MASS 2206-2047AB (Dupuy et al. 2009) observed at an air mass of 1.35 using the $R = 16.0$ magnitude science target as a guide star. The filled points are from observations in the K-band while the open points are from J, H and L' observations. The empirical quadratic fit is simply intended as a guide for the eye. (*Bottom*) Relative photometry error between binary stars (in magnitudes) versus Strehl ratio for the K-band observations. See the electronic edition of the *PASP* for a color version of this figure.

In order to be able to draw these conclusions they need to be able to make accurate measurements of positions, radial velocities, photometry, line-widths, etc. Strehl ratio, encircled energy, and FWHM are useful indicators of performance but they are

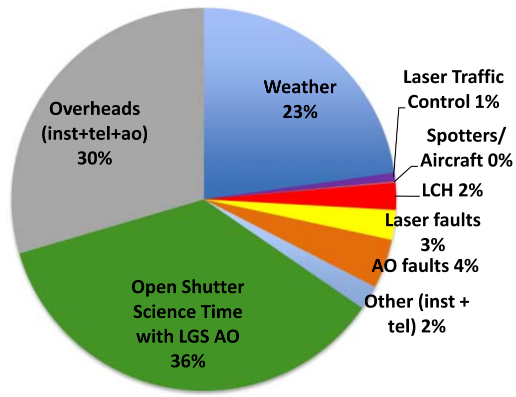

FIG. 12.—Pie chart of components of LGS AO observing time between 2005 and 2012 (provided by R. Campbell, WMKO). See the electronic edition of the *PASP* for a color version of this figure.

not sufficient to understand how the AO system will perform for a given science case. The AO and science community therefore needs to, and has begun to, develop error budgets for astrometry, photometry, faint companion sensitivity, etc., in order to derive the requirements on new AO systems.

4. *AO ought to provide a useful level of performance in moderate to poor atmospheric conditions*. Both Keck NGS and LGS AO provide high angular resolution in poor conditions but with reduced Strehl and a broadening of the diffraction-limited core. Performance and performance stability has generally improved with Keck LGS AO. The LGS is considerably brighter than most NGS so the high order correction is generally improved and, since the LGS is pointed directly at the science target, isoplanatic effects (other than tip-tilt) are removed. As one science example, the higher Strehl and Strehl stability with LGS AO has led to the ability to perform multi-year, precision astrometric measurements on the Galactic Center.

5. *AO performance ought to mitigate the effects of highly and rapidly variable atmospheric conditions*. It is doubtlessly true for all AO systems that if the conditions get worse the performance degrades even with reoptimization, and often observations taken under poor conditions are discarded in favor of data obtained under better conditions. The frequency with which data needs to be discarded has certainly been reduced in the transition from Keck NGS AO to LGS AO for the reasons stated in the previous item. The ability to change to observing targets or programs that have less stringent performance requirements certainly makes better use of poorer conditions; at Keck this must be done at the discretion of the observer as opposed to using a condition dependent observing queue.

6. *A telescope ought to be designed together with its AO systems*. Unfortunately, the design of the Keck AO systems began after the first Keck telescope was already on-sky. Luckily these telescopes have large Nasmyth platforms which became the homes for the AO systems. The existing telescopes and control systems did provide a large number of design constraints, but on

the other hand it was not necessary to wait for telescope design decisions to be made or for the telescope to be made operational. More important from the Keck perspective was the need to design science instruments, especially the Keck Interferometer, together with the AO systems. Also, it should be pointed out that the lack of a science quality instrument in the first 2 years of Keck AO science operation severely limited science productivity and operational completion of the facility.

7. *The operational effort to continually achieve optimal performance may be considerable*. The Keck experience is that a highly skilled and engaged AO operations team is critical to scientific success (Campbell et al. 2008). In WMKO's case the AO development team was able to work with the operations group to train personnel and to create an AO operations team. The interactions between operations and development make both teams stronger and more aware of the issues impacting scientific productivity. It also provides more depth when problems arise. A special feature at WMKO has been the ability to continue to develop the operational AO systems to achieve better performance or to implement new capabilities. This has been a challenge given the nightly use of the telescopes and the ~50% use of the Keck II AO system; however, it has been made possible by the ability to physically access the Nasmyth mounted systems, to remotely control the systems, and to be able to test and revert software while protecting the operational system through procedures and configuration control.

8. *AO systems ought to provide support for post-processing of data by enabling the PSF to be derived*. Members of the Keck AO user community are well aware of the value of PSF information and are working with the observatory to understand the requirements on PSF knowledge and to develop PSF reconstruction techniques as discussed in § 4.

6. CONCLUSIONS

The following items represent the author's attempt to draw some conclusions from the data provided in this article (the figures or tables used in drawing these conclusions are referenced in parentheses):

1. Keck NGS AO has been productive in both solar system and galactic science where bright enough NGS are available (Table 1 and Fig. 3). Exoplanet imaging and spectroscopy (Fig. 1), and follow-up imaging observations of stars identified to have exo-planets, has recently become a productive field for Keck NGS AO (Figs. 1 and 3).

2. The higher sky coverage and performance (with faint tip-tilt stars), offered by Keck LGS AO versus NGS AO, has opened up a much broader range of science, especially extragalactic science, to the WMKO community (Tables 1, 2, and Fig. 4).

3. The scientific demand for Keck LGS AO is high. Since 2006, ~30% of the Keck II science nights have been used for LGS AO observations versus ~15% for NGS observations (Fig. 6).

4. The near-infrared camera, NIRC2, has been and continues to be responsible for the largest number of refereed science papers using Keck AO data (Fig. 5). However, clearly the time allocation committees are valuing the science produced by OSIRIS since the number of LGS AO science nights awarded for OSIRIS proposals has slightly exceeded those awarded for NIRC2 proposals since 2006 (Fig. 6). It should be pointed out that many OSIRIS programs are multi-hour integrations on faint extra-galactic targets.

5. The near-infrared science instruments, with the exception of OSIRIS, that are used with Keck AO have comparable or better science productivity (papers per night) than the Keck seeing-limited near-infrared instruments (Fig. 7).

6. The papers that use Keck AO data are published in a range of astronomical journals with the majority (59%) being published in the Astrophysical Journal (Table 4).

7. The Keck AO systems are being used by a significant fraction of the astronomical community beyond the universities that have direct shares in WMKO (Table 5). Of the 609 unique authors on refereed papers using Keck AO data published in 2012, 39% were from other U.S. institutions and 31% were from non-U.S. institutions. As a side note: Many graduate students and postdocs have had the opportunity to observe with the Keck AO systems and to published papers or theses based on Keck AO data.

8. Producing scientifically productive LGS AO systems is challenging, as illustrated by the low science productivity of other LGS AO systems to date. The Keck II LGS AO system is by far the most productive LGS AO system in the world (Fig. 8). This is likely, at least partly, due to the performance (Figs. 9 and 10) and relatively high observing efficiency (Fig. 12) of the Keck system.

To conclude, the Keck II AO system has been a very productive scientific facility to date, as illustrated by the 412 astronomical papers published in refereed journals through 2012 based on data from this system. Much of this science could not have been produced without the high angular resolution offered by AO on a large telescope, and many of the targets could not have been observed without LGS AO. The scientific capabilities and performance of this system are continuing to be improved. The prospects for more cutting edge science from the Keck II and Keck I AO systems are extremely good.

A large number of people have contributed to the overall scientific success of the Keck II AO system from the AO and instrument developers, to the AO operations team, the funding sources, and the astronomical community that has used them so effectively.

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