LGS AO Science Impact: Present and Future Perspectives

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ABSTRACT
The recent advent of laser guide star adaptive optics (LGS AO) on the largest ground-based telescopes has enabled a wide range of high angular resolution science, previously infeasible from ground-based and/or space-based observatories. As a result, scientific productivity with LGS has seen enormous growth in the last few years, with a factor of \( \approx 10 \) leap in publication rate compared to the first decade of operation. Of the 54 refereed science papers to date from LGS AO, half have been published in the last \( \approx 2 \) years, and these LGS results have already made a significant impact in a number of areas. At the same time, science with LGS AO can be considered in its infancy, as astronomers and instrumentalists are only beginning to understand its efficacy for measurements such as photometry, astrometry, companion detection, and quantitative morphology. We examine the science impact of LGS AO in the last few years of operations, largely due to the new system on the Keck II 10-meter telescope. We review currently achieved data quality, including results from our own ongoing brown dwarf survey with Keck LGS. We assess current and near-future performance with a critical eye to LGS AO’s capabilities and deficiencies. From both qualitative and quantitative considerations, it is clear that the era of regular and important science from LGS AO has arrived.

Keywords: Adaptive optics, laser guide stars, high angular resolution, brown dwarfs, Keck Telescope

1. INTRODUCTION
Astronomers have envisioned using laser guide star adaptive optics (LGS AO) to achieve diffraction-limited observations from ground-based telescopes for over two decades.\(^1\)–\(^3\) (See Refs. 4 and 5 for a historical review.) The realization of this vision has required the dedication, talents, and resources of myriad individuals and organizations. LGS AO is now being used regularly to conduct a broad range of science. The promise of near diffraction-limited imaging and spectroscopy from the ground over most of the sky is coming to fruition. This heralds an important new capability for observational astronomy.

The purpose of this paper is to examine the science that has been done using LGS AO, with a critical eye to what has been achieved and what promises and challenges remain. Much has been accomplished since the last review of science from LGS (Ref. 6), which focused on publication output. Here, we go beyond mere productivity and examine the science impact of LGS as demonstrated in the record of published research.

2. LGS AO SCIENCE PRODUCTIVITY AND IMPACT
As of June 2008, five telescopes have generated astronomical science publications from LGS AO: the 1.5-meter Starfire Optical Range (SOR) Telescope in New Mexico;\(^7\) the 3-meter Shane Telescope at Lick Observatory in California;\(^8\) the 3.5-meter German-Spanish Astronomical Centre Telescope in Calar Alto, Spain;\(^9\) the 10-meter Keck II Telescope in Hawaii;\(^10\) and the 8.1-meter Gemini-North Telescope in Hawaii.\(^11\) The Starfire system used a Rayleigh-backscattered LGS, and the other systems use sodium laser guide stars.

In the first decade when LGS was available for astronomical science (1995–2004), science productivity was modest, amounting to 10 refereed papers from Starfire, Lick, and Calar Alto. In comparison, as of July 2002, after about a decade of science operation, AO systems had produced 144 refereed science papers, nearly all derived from natural guide star (NGS) AO systems.\(^12\) A non-comprehensive search of the NASA Astrophysical Data System (ADS) abstract database in 2006 indicates that the total number of AO science papers had about doubled.
since then, again dominated by NGS observations. The modest science productivity of LGS AO compared to NGS AO is no doubt due to the vastly greater complexity and cost of implementing LGS AO systems.

However, the last few years have seen enormous growth in LGS science productivity, as compiled using NASA ADS and summarized in Figure 1 (This compilation includes only papers focused on astronomical science. Refereed AO instrumentation, “first light” papers, and on-sky atmospheric calibration papers are not included — either way, these would amount to a minor perturbation.) Since 2005, there has been a surge in refereed publications, largely due to the sodium LGS AO system on the Keck II Telescope which accounts for 39 out of the 44 publications from 2005–2008. Some notable science highlights from LGS AO include:

- Identification of small moons around Jupiter Trojan asteroids and Kuiper Belt Objects and subsequent direct density determinations by Marchis et al. (Ref. 13) and Brown et al. (Refs. 14, 15);

- Measurement of the atmospheric properties and dynamical masses of brown dwarfs by Liu et al. (Refs. 16–18 and § 3);

- Discovery of spatially resolved photoevaporating gas structures around young pre-main sequence stars in the Orion Nebula Cluster by McCullough et al. (Ref. 19);

- Examination of the extended and/or time-variable emission around the Galactic Center by Ghez et al. (Ref. 20, 21) and Krabbe et al. (Ref. 22);

- Determination of the mass function and the proper motion of the Arches Cluster in the vicinity of the Galactic Center by Kim et al. (Ref. 23) and Stolte et al. (Ref. 24);

- Identification of the progenitor stars of Type II supernovae by combining Keck LGS imaging of the SN with pre-explosion images in the HST Archive by Gal-Yam et al. (Refs. 25, 26);

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• Measurement of the stellar velocity dispersion of a luminous quasar host galaxy by Watson et al. (Ref. 27);
• Measurement of the spatially resolved kinematics of \(z = 1.5 - 3\) star-forming galaxies by Wright, Law et al. (Refs. 28, 29).

Except for the Orion study which was done with the 1.5-meter Starfire Telescope and the quasar host galaxy result from the Gemini-North 8.1-meter Telescope, all of these results come from the Keck LGS system. This is not surprising, given this is the first facility LGS AO system on an 8–10 meter class telescope and has been in regular operation for 3+ years. As such, it provides a good illustration of the areas of science which astronomers are eager to explore using LGS. To illustrate the wide diversity of topics, Table 1 summarizes the science areas that have been addressed with the Keck system so far. Galactic science provides the majority of the science, and within that category, half of the papers relate to brown dwarfs and/or low-mass stars. However, a significant fraction (≈40%) of papers are in the area of extragalactic science, a notable (and anticipated) change from science done with NGS.

| Area           | Number of Papers | Sub-Topic (Number of Papers)                        |
|----------------|------------------|----------------------------------------------------|
| Galactic       | 20               | Brown dwarfs and low-mass stars (N=11)             |
|                |                  | Galactic Center (N=6)                             |
|                |                  | Compact objects (N=2)                             |
|                |                  | Star formation (N=1)                              |
| Extragalactic  | 15               | High-redshift galaxies (N=6)                       |
|                |                  | Gravitational lensing (N=3)                        |
|                |                  | Stellar populations (N=3)                          |
|                |                  | Supernovae (N=3)                                  |
| Solar System   | 4                | Kuiper Belt (N=3)                                 |
|                |                  | Asteroids (N=1)                                   |

While the quantity of publications is an unambiguous metric of science output, a more difficult issue to quantify is whether the LGS AO science being done has been scientifically important/impactful. As one (and only one!) line of analysis, we examine the citation counts of LGS science papers in light of the study by Pearce. He has assembled the distribution of citation counts as a function of year since publication, allowing us to derive a citation ranking of LGS science papers relative to all astronomical science papers published at the same time. Table 2 presents the top cited LGS science papers, both in terms of total citations and relative ranking. Overall, a number of recent papers have been in the top 1–3% of citations relative to their contemporary publications. (In the spirit of measuring LGS science impact, the Table only included papers whose science content was substantially based on LGS observations, not ones where the LGS data play an inconsequential role. This criterion excludes one highly cited paper, Ref. 31, which would have placed 2nd on the list with 34 citations in one year since publication.)

### 3. SUMMARY OF KECK LGS PERFORMANCE

#### 3.1 A High Angular Resolution Survey of Field Brown Dwarfs

To illustrate what is currently possibly with LGS, we examine the on-sky performance of the Keck LGS system. Since the inception of the Keck system for open science use in 2005, my collaborators and I have been conducting a high angular resolution near-IR study of nearby brown dwarfs. Our goals are (1) to assess the binary frequency of ultracool dwarfs; (2) to test atmospheric models with these coeval systems, e.g., as associated with the abrupt spectral transition from the L dwarfs to the T dwarfs; (3) to search for exceptionally low-temperature companions; and (4) to find and monitor substellar binaries suitable for dynamical mass determinations.
Table 2. Top-cited science papers from LGS AO. Some paper titles have been abbreviated. “N(cite)” gives the number of citations, based on data from NASA ADS. “Rank” gives the citation counts of each paper relative to other astronomy papers published at the same time based on the compilation of Pearce (Ref. 30), e.g., 99% means that the paper is more highly cited than nearly all papers published at the same time. “Field” gives the area of study: “SS” = solar system, “Gal” = galactic, “Xgal” = extragalactic. “N(obj)” indicates the number of science targets/fields observed with LGS. Note that NASA ADS is incomplete for citations of solar system papers, hence the “>” for the last paper.

| N(cite) | Rank | Year | Authors: Title, Journal | Tel | Field | λλ | N(obj) |
|--------|------|------|--------------------------|-----|-------|----|-------|
| 42     | 90%  | 1995 | McCullough et al., Photoevaporating Stellar Envelopes Observed with Rayleigh Beacon AO, ApJ | SOR | Gal | Hα | 1 |
| 30     | 99%  | 2007 | Gal-Yam et al., On the Progenitor of SN 2005gl and the Nature of Type IIn SN, ApJ | Keck | Xgal | K′ | 1 |
| 30     | 98%  | 2006 | Liu et al., A Novel T Dwarf Binary and the Potential Role of Binarity in the L/T Transition, ApJ | Keck | Gal | JHK | 1 |
| 30     | 97%  | 2005 | Ghez et al., LGS AO of the Galactic Center: Sgr A*’s IR Color and its Extended Red Emission, ApJ | Keck | Gal | KL′ | 1 |
| 30     | 97%  | 2005 | Liu et al., Kelu-1 is a Binary L Dwarf: First Brown Dwarf Science with LGS AO, ApJ | Keck | Gal | JHK | 1 |
| >18    | >97% | 2006 | Brown et al., Satellites of the Largest Kuiper Belt Objects, ApJ | Keck | SS | K′ | 4 |

LGS AO represents a major advance for this science area. Most known brown dwarf binaries have separations of <0.3″, hence the need for high angular resolution imaging to find and characterize them via resolved photometry and spectroscopy, but they are too optically faint for natural guide star AO. Our observations have achieved 3–4× the angular resolution at K-band (2.2 μm) compared to HST and thus are more sensitive to close companions. In addition, the ability of Keck LGS AO to find tighter binaries means that systems with much shorter orbital periods than the current sample can be found and expeditiously monitored. Finally, many of the key spectral diagnostics of brown dwarfs are in the infrared and thus probing the atmospheric properties of these objects with resolved colors and spectra of binaries is well-suited to current LGS capabilities.

Our brown dwarf imaging survey provides an excellent dataset for assessing typical Keck LGS performance in the case of off-axis observations, namely the situation where the LGS is pointed to the science target but tip-tilt sensing and correction are derived from an adjacent field star. Brown dwarfs are far too optically faint to serve as their own tip-tilt references and hence the need for a nearby tip-tilt star – this is the same observing situation as for many extragalactic LGS applications and thus provides a good reference point. For Keck, the tip-tilt star must be within 60″ of the science target – in practice, we find that this results in a sky coverage fraction of about 2/3 for an estimated K-band Strehl ratio of >0.2. Since targets for our brown dwarf program span most of the sky (except for avoidance of the galactic plane), this 2/3 sky coverage estimate is a fair representation of the fraction of any set of generic targets that can be imaged with LGS.

Figure 2 summarizes the image quality of a subset of our Keck LGS observations of nearby brown dwarfs, spanning multiple observing runs from 2005–2007. No bad data have been censored, so a mix of seeing conditions, off-axis tip-tilt star properties, and technical performance (e.g., LGS projected power and sodium light return flux) are represented. (See also Ref. 6 for more performance descriptions.) The median K-band image FWHM for our survey is 0.076″ with a best value of 0.051″. The median K-band Strehl is 0.17 with a best value of 0.34.

LGS images are naturally time-variable, and the shape and detailed structure of the PSF changes in every image. Figure 2 provides one representation of this PSF variability, plotting histograms of the fractional RMS deviations in K-band FWHM and Strehl ratios. Typically, each of our brown dwarf datasets constitutes a series of 6–12 images, each with a integration of about 1 min and total elapsed time of about 15–30 min. Over these time scales, the plotted histograms show significant FWHM and Strehl variations. This is obviously a challenge
Figure 2. Summary of Keck LGS AO K-band (2.2 μm) performance, based on our near-IR imaging survey of brown dwarfs (Liu et al., in prep). No bad data have been censored, so the compilation comprises a mix of seeing conditions, target airmasses, and technical performance. Top panels: Histogram of K-band FWHM and its fractional RMS variation within a given dataset. Typically each dataset is composed of 6–12 individual images taken over an elapsed time of 10–20 minutes. The median FWHM is 0.076′′ with a median RMS variation of 5%. Bottom panels: Same histograms for K-band Strehl. The median Strehl is 0.17 with an RMS variation of a factor of 1.19 (e.g., Strehl = 0.17 ± 0.03).

for science programs requiring a stable PSF.

Despite the notable PSF fluctuations, high precision science can be with Keck LGS data. For example, we have been using LGS to carefully monitor the orbits of binary brown dwarfs in order to determine their dynamical masses and thereby test theoretical models. Despite the hundreds of brown dwarfs that have been identified and had their spectrophotometric properties characterized, direct measurements of their most fundamental property, namely their mass, are sorely lacking. Typical estimated orbit periods are a decade a more, but many of the
Figure 3. First dynamical mass determination for a binary T dwarf, the T5.0+T5.5 binary 2MASS J1534-2952AB (Ref. 18). Six epochs of data from Keck LGS are combined with HST archival data to form a dataset from 2000-2008 that spans about 50% of the 15-year orbital period. Through careful analysis of the binary images with PSF fitting, the Keck LGS data achieve sub-milliarcsecond relative astrometry of the two components. The total mass is $59 \pm 3 \, M_{\text{Jup}}$. This is the first field binary for which both components are directly confirmed to be below the stellar/substellar limit ($\lesssim 75 \, M_{\text{Jup}}$). This is also the coolest and lowest mass binary with a dynamical mass determination to date. The left plot shows the relative astrometry and best-fitting orbit. The right plot shows the separation measurements compared to the best-fitting orbit (solid line) and two alternative orbital periods of similar total mass (dashed and dotted lines). The right bottom sub-panel shows the residuals between the observations and the predictions from the orbits.

binaries were discovered $\gtrsim 5$ years ago with HST and thus multi-epoch LGS followup is well-suited to dynamical mass determinations.

Figure 3 shows an example of what is possible, presenting the orbit of the T5+T5.5 binary 2MASS J1534-2952AB by Liu, Dupuy and Ireland (Ref. 18). This is the first dynamical mass determination for a binary T dwarf, the coolest and least luminous class of brown dwarfs. There are two stars within 6″ of 2MASS J1534−2952AB which we use as PSFs to deblend the light of the two binary components. Through extensive Monte Carlo testing of different deblending methods applied to simulated images of binary stars constructed from the single PSFs, we are able to measure the relative position and orientation of the components to 0.3–0.7 mas and 0.2–0.7° RMS at $K$-band. The precision of the best measurements is such that atypical sources of uncertainty need to be considered, including:

1. The calibration of the instrumental plate scale and orientation can introduce additional uncertainty, since these values for the Keck facility near-IR camera are known to about 1 part in $10^{-3}$ and 0.1°, respectively.

2. The differing spectral types of the two components means that the light from each is subjected to a slightly different amount of differential chromatic refraction (DCR). Given the sky orientation of the binary (just about North-South), the declination of the target ($\delta = -29^\circ$ meaning the smallest possible airmass for Keck observing is 1.55), and the fact that we observe it near transit (for best AO performance), the DCR causes the separation of the binary to appear slightly smaller at $H$ and $K$-bands and slightly larger at $J$-band compared to the true position as would be observed at zenith. The amplitude of the DCR effect is about 0.3 mas, much smaller than the measurement errors at most (but not all) of the Keck epochs. However, the effect is a systematic one so we correct the relative astrometry of the two components based on synthetic photometry from T dwarf spectra. (Since T dwarfs have suppressed flux at the longward portion of the $K$-band, the DCR is smaller than it would be for L dwarfs observed at the same airmass.)
The quality of the Keck LGS astrometry equals or exceeds that available for the same target from HST, though at the very smallest separations (≈FWHM) HST data still have an advantage since the very stable HST PSF can be simulated to high fidelity and then fitted to tight binary images (e.g., Ref. 18). However, LGS AO provides the necessary long-term platform for synoptic monitoring of visual binaries, especially since the required amount of observing time at each epoch is relatively modest but many epochs are needed. This in contrast to HST where target acquisition is slow and monitoring a populous sample over many epochs is telescope time-intensive.

3.2 Review of Published Keck Performance

To further summarize the current capability, Table 3 provides a summary of achieved Keck LGS performance as presented in the published science papers. Obviously this is a heterogeneous assemblage from both the standpoint of the observations and the subsequent analysis, but it does provide “ground truth” of the quality of on-sky data that has proven suitable for publication. We consider several types of measurements that readily lend themselves to quantitative uncertainties (as opposed to more difficult measurements to quantify such as, e.g., morphological studies of resolved objects):

- **Relative photometry**: the flux of a science target relative to other sources in the same image of known brightness (e.g., from 2MASS);
- **Absolute photometry**: the absolute flux of a science target as directly measured from the images of the target and then compared to a photometric calibrator star observed contemporaneously (but not simultaneously);
- **Relative astrometry**: the location of sources in an LGS dataset relative to each other.
- **Absolute astrometry**: the location of sources in a LGS dataset as referenced to absolute astrometry tied to an external dataset (e.g., HST).
- **Binary (relative) photometry**: the relative flux ratio of a binary;
- **Binary (relative) astrometry**: the separation and position angle of a binary;
- **Crowded field astrometry**: the positions and/or proper motions for a field with many sources (e.g., star clusters and resolved nearby galaxies);
- **Crowded field (relative) photometry**: the same as relative photometry above, except for a field with many sources;
- **Crowded field (absolute) photometry**: the same as absolute photometry above, except for a field with many sources.

Table 3 shows that high quality measurements have been achieved with LGS, especially for relative measurements. In the published papers, the most measurements are available for relative photometry and astrometry of low-mass binaries, since this is a class of science that readily benefits from LGS.

4. CHALLENGES AND SOLUTIONS

There are obviously still a number of challenges to be overcome in order for LGS AO be considered a regular component of every astronomer’s “toolkit.” As another examination of science being done with LGS, Figure 4 shows a histogram of the number of science targets and/or (substantially different) pointings in an LGS paper — most LGS papers (77% ± 12%) are focused on a single object/pointing. For reference, we plot to the same histogram for a sample of observational papers selected from randomly chosen astro-ph daily email notifications from 2006. The distribution of the number of targets/fields is similar for both the LGS and astro-ph samples, in that most papers are focused on a small number of objects. However, a two-sided Kolmogorov-Smirnov test shows only a 17% probability that the two samples are drawn from the same parent population. The LGS sample has a somewhat larger fraction of papers based on only a single object/field. Also, while the most populous survey in any LGS paper is composed of 18 objects, the astro-ph sample has 19% ± 5% of its papers containing more
than 18 objects. The differences in the two samples is no doubt due to several factors, including (1) the present technical difficulties of using LGS for “survey-style” science, (2) conservative planning on the part of new LGS observers, and/or (3) the desire to promptly observe notable objects with a brand-new observational capability (a.k.a., “low-hanging fruit”).

As seen in the published work to date, a number of outstanding challenges exist for carrying science measurements. An incomplete list includes:

- **Relative photometry and astrometry at small separations**: Many of the Keck LGS papers are concerned with scenes that involve measuring relative fluxes and/or positions of sources at small separations, e.g., brown dwarf binaries, the Galactic Center, gravitational lenses, and resolved stellar populations. There are substantial gains to be realized from reduction in the measurement uncertainties, e.g., by increasing the stability of the LGS AO PSF and/or knowledge of the real-time achieved PSF. For instance, for binary measurements LGS has achieved as good as $\approx 0.3$ mas, but more accurate astrometry would lead to more accurate dynamical masses with a shorter time baseline.

From the standpoint of photometry, most science programs require a bare minimum of $\approx 0.1$ mag photometric uncertainty, e.g., since the IR colors of stars span only a few tenth’s of a magnitudes. A level of $\approx 0.03$ mag is sufficient for many quantitative applications, e.g., spectral type estimates for binaries and color-magnitude diagrams of resolved stellar populations, and LGS AO has already demonstrated this level of accuracy. But it has yet to achieve the $\lesssim 0.01$ mag level routinely achieved with modest effort from the ground and space.

- **Absolute photometry in sparse fields**: None of the published Keck LGS papers attempt to do direct photometric calibration of imaging data, but rather calibrate all data against existing seeing-limited data.

- **Instrumental astrometric calibration**: About half the Keck LGS papers involve high precision astrometry, for programs involving solar system bodies, brown dwarf binaries, the Galactic Center, and SN progenitors, and these programs are likely to continue to be important long-term science. The current Keck facility camera calibration has been adequate, but improving this to a level of $\lesssim 10^{-3}$ in pixel scale and $\lesssim 0.1^\circ$ would be valuable.

- **PSF variability and uncertainty**: Significant quantitative science has been done *despite* the temporal and spatial variability of the LGS AO PSF. In some cases, the science programs benefited from having one
or more PSF stars in the same field as the science target; this is especially valuable for programs needing precise measurement such as astrometric monitoring or quantitative analysis of complex morphologies (e.g., Refs. 18, 20, 24, 36). In other cases, PSF images taken near-contemporaneously have been used for modeling; while less optimal, this may be suitable for programs where basically the average bulk properties of the PSF (e.g., encircled energy as a function of radius) are more important than the detailed structure, such as high-redshift galaxies where the relevant angular scales are larger than diffraction-limited PSFs. The reliability of such techniques can be validated through careful modeling of PSF effects on the science data (Ref. 37). One example of this has been the work of Sheehy and collaborators (Ref. 38), who tackle a specific PSF aspect needed for their science program, namely the determination of aperture corrections for crowded field photometry. Similarly, studies by Steinbring et al., Britton, Cresci et al., and Cameron et al. (Refs. 39–42) have addressed methods to account for PSF spatial variations in NGS AO data and seem valuable for extending to LGS AO data.

- **Non-redundant aperture masking:** one promising technique is the application of non-redundant aperture masking to LGS observations. By replacing the usual clear pupil of the science instrument with a milled plate of holes that form a series of non-redundant baselines, atmospheric and AO noise can be largely eliminated. This enables interferometric-style imaging over a small FOV but to very tight separation ($\lambda/D$). Aperture masking has been amply used with Keck NGS AO (e.g., Refs. 43, 44). The first application of this technique with LGS AO is presented by Burgasser, Liu, Ireland et al. (Ref. 45), where aperture masking was used to obtain $\approx 3$ mag gain in contrast over LGS direct imaging to search for faint companions at radii $\leq 2\times\text{FWHM}$. The limitation of the method is that $\approx 90\%$ of the instrument pupil plane is blocked out, meaning the method is restricted to IR bright objects. However, it does provide a promising method for achieving much greater contrast at small separations compared to direct imaging.

Since the previous review on LGS science (Ref. 6), it is clear that LGS science has leaped forward. The last few years have witnessed a veritable boom in science from LGS, as seen in a doubling of science papers in the only last 2 years and an order of magnitude increase in publication rate compared to first decade of LGS. The science impact of LGS AO has been significant in a small but important subset of fields and is gaining use in other areas. The Keck LGS system has provided most of these current science gains, and we can eagerly expect a similarly large leap as the Gemini-North and VLT systems come into regular science use. From both qualitative and quantitative considerations, it is clear that the era of regular and important science from LGS AO has arrived.

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| Property                          | Measurement Uncertainty (\(\lambda\)) | Science Object                                      | Ref |
|----------------------------------|----------------------------------------|-----------------------------------------------------|-----|
| Photometry: Relative            | \(\approx 0.05\) mag \((K)\)           | Grav. lens, 2" size                                 | 36  |
|                                 | \(\approx 0.03\) mag \((K)\)           | Wide (11") binary                                   | 46  |
|                                 | \(\approx 0.14\) mag \((H)\)           | High-\(z\) supernova, \(H \sim 24\)               | 47  |
|                                 | \(\approx 0.15\) mags \((K)\)          | Grav. lens w/2 field stars                          | 48  |
|                                 | 0.06–0.11 mags \((JHK)\)               | Galactic high energy source                         | 49  |
| Photometry: Absolute            | n/a                                    |                                                     |     |
| Astrometry: Relative            | \(\approx 1.5\) mas \((K)\)           | Grav. lens, 2" size                                 | 48  |
|                                 | \(~5\) mas \((K)\)                     | Wide (11") binary                                   | 46  |
|                                 | 40–90 mas \((H)\)                     | Galactic high energy source                         | 49  |
| Astrometry: Absolute            | 0.01" \((K)\)                         | Resolved galaxy + SN                               | 26  |
|                                 | 0.1" \((K)\)                          | Galactic high energy source                         | 49  |
|                                 | 0.01"\((K)\)                          | Resolved galaxy + SN                               | 25  |
| Binary (relative) photometry    | \(\approx 0.01\) mag \((JHK)\)        | Binary: \{\(\approx 0.2", \Delta \text{mag} \approx 0.3\}\} | 18  |
|                                 | \(\approx 0.05\) mag \((HK)\)         | Binary: \{\(\approx 0.1", \Delta \text{mag} \approx 0.3\}\} | 18  |
|                                 | \(\approx 0.3\) mag \((K)\)           | Binary: \{\(\approx 0.5", \Delta \text{mag} \approx 4.2\}\} | 15  |
|                                 | \(\approx 0.1–0.3\) mag \((K)\)       | Binary: \{\(\approx 1.2", \Delta \text{mag} \approx 1.4\}\} | 15  |
|                                 | 0.04–0.09 mags \((JHK)\)              | Binary: \{\(\approx 1.2", \Delta \text{mag} \approx 1.4\}\} | 15  |
|                                 | 0.05–0.06 mags \((JHK)\)              | Binary: \{\(\approx 0.07", \Delta \text{mag} \approx 1.2\}\} | 50  |
|                                 | 0.05 mags \((JK)\)                    | Binary: \{\(\approx 0.37", \Delta \text{mag} \approx 1.5\}\} | 50  |
|                                 | 0.02–0.04 mags \((JHK)\)              | Binary: \{0.29", \(\Delta \text{mag} \approx 0.5\)\} | 16  |
|                                 | 0.04–0.05 mags \((JHK)\)              | Binary: \{0.11", \(\Delta \text{mag} \approx 0.5\)\} | 17  |
| Binary (relative) astrometry    | \(\approx 0.3–1.5\) mas \((JHK)\)    | Binary: \{\(\approx 0.2", \Delta \text{mag} \approx 0.3\}\} | 18  |
|                                 | \(\approx 0.5–1.0\) mas \((HK)\)      | Binary: \{\(\approx 0.1", \Delta \text{mag} \approx 0.3\}\} | 18  |
|                                 | \(\approx 10–50\) mas \((HK)\)        | Binary: \{\(\approx 0.5", \Delta \text{mag} \approx 4.2\}\} | 51  |
|                                 | \(\approx 50\) mags \((K)\)           | Binary: \{\(\approx 0.07", \Delta \text{mag} \approx 0.9\}\} | 52  |
|                                 | 4 mags \((JHK)\)                      | Binary: \{\(\approx 1.2", \Delta \text{mag} \approx 1.4\}\} | 15  |
|                                 | 2.5 mags \((H)\)                      | Binary: \{\(\approx 0.07", \Delta \text{mag} \approx 1.2\}\} | 50  |
|                                 | 3 mags \((K)\)                        | Binary: \{\(\approx 0.37", \Delta \text{mag} \approx 1.5\}\} | 50  |
|                                 | \(\approx 20–30\) mags \((K)\)        | Binary: \{\(\approx 0.6–1.3", \Delta \text{mag} \approx 4\}\} | 14  |
|                                 | 2 mags \((K)\)                        | Binary: \{0.29", \(\Delta \text{mag} \approx 0.5\)\} | 16  |
|                                 | 5 mags \((H)\)                        | Binary: \{0.11", \(\Delta \text{mag} = 0.7\)\} | 17  |
| Crowded field astrometry        | 2 mags \((K)\)                        | Star cluster: \{\(K < 20.5\) mag, \(\Sigma_* \approx 4/\square \)\}\} | 24  |
| Crowded field relative phot      | \(<0.01\) mag \((HK)\)                | Stellar pops: \{\(HK \leq 19\) mag, \(\Sigma_* \approx 4/\square \)\}\} | 53  |
|                                 | \(\approx 0.05\) mag \((HK)\)         | Star cluster: \{\(HK \leq 19\) mag, \(\Sigma_* \approx 4/\square \)\}\} | 53  |
|                                 | \(\approx 0.05\) mag \((HK)\)         | Gal Center: \{\(HK \leq 19\) mag, \(\Sigma_* \approx 4/\square \)\}\} | 20  |
| Crowded field absolute phot      | \(\leq 0.04\) mag \((H, K)\)          | Stellar pops: \{\(HK \leq 22\) mag, \(\Sigma_* \approx 4/\square \)\}\} | 53  |
|                                 | 0.05 mag \((H)\)                      | Stellar pops: \{\(H \leq 20\) mag, \(\Sigma_* \approx 3/\square \)\}\} | 38  |
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