**RESPONSE TO WHITE PAPER QUESTIONS**

<u>Complete the below fields. The white paper will not be accepted without all fields completed.</u>


- Principal Author: *Andersson, B-G*
- Today's Date:*10/05/14*
- Institution of Principal Author: SOFIA Science Center, Universities Space Research Association

Co-Authors:
Adamson, Andy, Gemini Observatory
Bjorkman, Karen S., University of Toledo
Chiar, Jean E., SETI Institute
Clemens, Dan P., Boston University
Hines, Dean C., Space Telescope Science Institute
Hoffman, Jennifer L., University of Denver
Jones, Terry J., University of Minnesota
Lazarian, Alexandre, University or Wisconsin - Madison
Packham, Chris, University of Texas, San Antonio
Vaillancourt, John E., SOFIA Science Center/USRA
Wiktorowicz, Sloane J., University of California, Santa Cruz
Wisniewski, John, University of Oklahoma
Whittet, Douglas C.B., Rensselaer Polytechnic Institute.

- E-mail Address: bg@sofia.usra.edu

- Paper Title (if applicable): **The need for general-use polarimeters in the era of LSST.**

## WHITE PAPER QUESTIONS

The National Academies' OIR System Study Committee is charged with identifying the principal federal and non-federal capabilities in the U.S. OIR System and making strategic recommendations to optimize the System for the best science return. It is vital for the committee to receive community input, so we welcome brief White Papers on any related topics of interest. Questions that might be addressed include, **but are not limited to**, the following:

1. What O/IR capabilities are you using, are you planning to use, and will you need through the LSST era?

2. Do you have access to the O/IR capabilities you currently need to conduct your research, e.g. through a proposal process, through collaborators, or via data archives? If not, what is missing?

3. Comment on the need for the U.S. community's access to non-federal O/IR facilities up to 30 meters in size.

4. What could be done, outside of increased funding, that would enable the U.S. astronomical community to realize the goals of the decadal surveys at OIR wavelengths?

5. What is the role that a national observatory should have in an effective ground-based OIR system?

6. What are the U.S. long-term data management, archiving, and mining needs in ground-based O/IR astronomy, including those for LSST?

7. Given the increasing complexity of astronomical instrumentation, where should new major instruments be built (e.g. universities, national labs, collaborations)? How much instrument duplication is desirable or sustainable across different facilities of similar aperture?

8. How can the community ensure that future generations of astronomers have relevant instrumentation, observing, and software skills for the frontier science of tomorrow?

9. Comment on any needed evolution in human astronomical infrastructure, that is, the efficiency of sustaining instrumentation, data, or software teams in centers of excellence relative to assembling the needed skill sets from across the community.

10. What types of scientific and observing coordination among the various NSF telescopes (including Gemini and LSST) and non-federal facilities are the most important for making scientific progress in the next 10-15 years? How can such coordination best be facilitated?

11. Additional related topics.

*Provide your responses below those questions you wish to answer. Please limit your entire response to 2 single-spaced pages, Time New Roman font, 12-point size.*

**The need for general-use polarimeters in the era of LSST.**

Polarimetry constitutes the third leg of the astronomical research tripod. In addition to photometry and spectroscopy, unique information about celestial objects and processes is gleaned through analysis of polarized light. Polarization studies are crucial for understanding the dynamics of the universe and have: established the Unified Model of AGN; revealed the elusive magnetic field in the Milky Way and external galaxies; and mapped key features on unresolved stars. Polarimetry, across a wide range of wavebands, reveals key behaviors and insights, and cannot be replaced by imaging and/or spectroscopy alone.

Polarimetry is practiced across the full range of accessible wavelengths, from radio through gamma rays. At some wavelengths, the U.S. leads the world in polarimetric capabilities and investigations, including ground-based radio with the VLA and VLBA. In ground-based O/IR astronomy, the situation is considerably worse, with only a single polarimeter broadly available to the community, on one medium-to-large telescope. In contrast, Canadian and European astronomers have used their access to a wide array of state-of-the-art polarimeters to vault far past the U.S. in vital science areas. The international vitality of the technique is reflected in the recent submission of a polarimetric mission proposal, "***Arago***" (PI. C. Neiner) to the ESA M4 competition. As is apparent in Table 1, which lists O/IR polarimetric capabilities on major telescopes, the situation in the U.S. is extreme and threatens long-term damage to U.S. astronomy, as students receive scant exposure to polarimetric techniques and the scientific harvest they offer. The 2010 Decadal Survey of Astronomy and Astrophysics "*New Worlds, New Horizons in Astronomy and Astrophysics"* acknowledged in the "Panel on the Galactic Neighborhood" the importance of polarimetry, including for the study of magnetic fields. Without new community-accessible instruments, this cannot be addressed. And, without access to modern polarization instruments on competitive-sized telescopes, questions of data management, builders of instruments, and possible centers of excellence are all moot.

**Table 1: O/NIR polarimeters on 2+ m telescopes**

| Telescope | Ap. [m] | Instrument | Waveband | Pol. Mode | US Access? |
|---|---|---|---|---|---|
| N.O.T. | 2.5 | ALFOSC, NOTCam | Opt., NIR | Imaging/Spec. | No |
| Shane (Lick) | 3.0 | Kast[1] | Opt. | Spec | Private |
| CFHT | 3.6 | ESPaDOnS | Opt. | Spec. | No |
| WHT | 4.2 | ISIS, LIRIS | Opt., NIR | Imaging/Spec. | No |
| MMT | 6.5 | MMTPOL | NIR | Imaging | Private |
| **Gemini South** | **8.1** | **GPI** | **NIR** | **Spec.** | **Yes** |
| VLT | 8.2 | FORS2, NACO | Opt, NIR | Imaging/Spec | No |
| LBTO | 8.4 | PEPSI | Opt. | Spec. | Private |
| Keck | 10.0 | LRIS | Opt. | Spec. | Private |
| GTC | 10.4 | CanariCam | MIR | Imaging/Spec. | No |

In addition to widening discovery space, polarimetry has direct synergies with the Large Synoptic Survey Telescope. Two characteristic features of LSST science are large area surveys and time-domain astronomy; polarimetry contributes to both in unique ways.

Continuum and line polarization probe stellar and interstellar processes in complementary ways. Due to the varying opacity across the O/NIR, spectral coverage is critical. **Therefore, imaging and spectro-polarimetry capabilities across a broad spectral range are necessary to enable**

[1] Slated for closure/decommissioning

**high-impact, unique science,** including the following examples.

A defining large-scale feature of the Galaxy is its magnetic field, which is crucial in energy transport[1,2], cosmic ray propagation[3] and star-formation[4], and is uniquely traceable through O/IR polarimetry. With the advent of an observationally well supported theory of interstellar grain alignment[5], dust-induced polarimetry is now on a solid theoretical footing, and can be used to trace magnetic field structures and the field strengths, from the diffuse to the densest media, as well as characterize the foreground dust and field properties affecting the Cosmic Microwave Background radiation. Large-scale polarization mapping in the optical[6] will complement the NIR GPIPS survey[7] and low-resolution FIR[8] polarization surveys to reveal and characterize the field in lower extinction material with exquisite detail. For areas of particular interest, such as around bright sources[9] and in the "polarization holes" of deep starless clouds[10], polarimeters on large telescopes are needed to measure enough faint sources to allow us to probe fields to the highest extinctions. Lessons learned from detailed Galactic studies will be applied to the understanding of cosmic galaxy evolution.

Polarimetry provides unique access to processes in unresolved non-axisymmetric objects, from Active Galactic Nuclei to circumstellar and proto-stellar disks, exoplanets, supernova ejecta and active stars. Spectro-polarimetry will allow us to classify new objects discovered by LSST and characterize their 3-D structures as they vary with time.

We now know that most galaxies contain supermassive black holes[11] (SMBHs) and that the SMBH mass correlates with the larger scale mass of the galaxy[12]. However, why do not all galaxies show AGN activity? Polarimetry separates the light scattered from the central engine from the overall flux from the region, enabling direct searches of the central regions of AGN to find obscured SMBHs. At present, the number of accessible sources is sharply limited. The key action is at higher redshifts, and this requires polarimetry instruments on big telescopes.

Polarimetry provides powerful diagnostics for circumstellar disks across a broad range of environments, yielding model constraints not otherwise obtainable. Spectro-polarimetry directly measures disk spatial orientation and constrains disk geometry[13], temperature, composition, ionization state, density, and velocity field. It also provides a finer probe of time-variable behavior within the disk itself than does spectroscopy alone. Magnetic fields generate variability in YSOs and stars through magneto-rotational interactions. These include stellar dynamos, accretion rate variations driven by mass transport in the disk (Balbus-Haley effect), and accretion processes in magnetic cataclysmic variables [14].

The extended atmospheres of close-in exoplanets should show both Rayleigh scattering[15,16] in the blue and polarized signatures of large cloud particles in the red. Scattering by ~1 μm cloud particles depends on the size, shape, and index of refraction (e.g., discovery of $H_2SO_4$-$H_2O$ clouds in Venus via polarimetry[17]). Therefore, polarimetry is crucial in understanding exoplanetary atmospheres, as clouds are expected to be common there[18]. On the largest telescopes, spectro-polarimetry may reveal the composition of exoplanet atmospheres.

Polarimetry also probes structures in stellar environments, including clumpy winds in luminous blue variables[19], aspherical mass loss in single stars and binary systems[20], asphericities in post-AGB stellar winds [21] and multi-layered ejecta in supernova explosions[22,23].

Polarimetry is an ideal tool to trace such spatial and time variable phenomena, and thus complements and contributes critically to the survey and time domain astronomy mission of the LSST.

**References:**

[1] Slavin, J.D., 1989, ApJ, 346, 718.
[2] Fox, A.J., Savage, B.D., Wakker, B.P., Tripp, T. M. & Sembach, K.R., 2006, ASPC, 348, 385.
[3] Yan, H. & Lazarian, A., 2008, ApJ, 673, 942.
[4] Crutcher, R.M., Hakobian, N., & Troland, T.H. 2009, ApJ, 692, 844.
[5] Andersson, B-G, Lazarian, A. & Vaillancourt, J.E. 2015, ARA&A, in press.
[6] Berdyugin, A.; Piirola, V.; Teerikorpi, P., 2014, A&A 561, 24
[7] Clemens, D.P., Pinnick, A.F., Pavel, M.D., & Taylor, B.W. 2012, ApJS, 200, 19
[8] Planck Collaboration XIX, 2014, arXiv:1405.0871
[9] Andersson, B-G, Pintado, O., Potter, S.B., Straižys, V., & Charcos-Llorens, M. 2011, A&A, 534, A19
[10] Alves, F.O., Frau, P., Girart, J.M., et al. 2014, A&A, submitted
[11] Magorrian, J., et al. 1998, AJ, 115, 2285
[12] Kormendy, J. 2004, in Coevolution of Black Holes and Galaxies, ed. L.C. Ho (Cambridge: Cambridge Univ. Press)
[13] Quirrenbach, A., et al. 1997, ApJ, 479, 477
[14] Butters, O.W., Katajainen, S., Norton, A.J., Lehto, H.J. & Piirola, V., 2009, A&A, 496, 891.
[15] Berdyugina, S.V., Berdyugin, A.V., Fluri, D.M., & Piirola, V., 2011, ApJ, 728, L6
[16] Wiktorowicz, S.J. 2009, ApJ, 696, 1116
[17] Hansen, J.E., & Hovenier, J.W. 1974, Journal of Atmospheric Sciences, 31, 1137
[18] Kreidberg, L., Bean, J.L., Désert, J.-M., et al. 2014, Nature, 505, 69
[19] Davies, B., et al. 2005, A&A, 439,1107
[20] Ignace, R., et al. 2009, AJ, 137, 3339
[21] Ueta, T., et al. 2007, AJ, 133, 1345
[22] Wang, L. & Wheeler, J.C., 2008, ARA&A, 46, 433.
[23] Mauerhan, J. et al. 2014, MNRAS, 442, 1166