Keck Interferometer V^2 Science

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ABSTRACT

We summarize the status of the Keck Interferometer in V^2 mode, and science results recently obtained.

Keywords: Keck Interferometer, optical interferometry, young stars, pre-main sequence binaries, circumstellar disks, eclipsing binaries, Wolf-Rayet stars.

1. INTRODUCTION

The Keck Interferometer (KI) is a NASA project to perform optical interferometry with the two 10 m diameter Keck telescopes. The Keck telescopes are separated by a physical baseline of B=85 m, therefore the fringe spacing (λ_0/B, which can be used as measure of resolving power) of the interferometer is 5 milliarcseconds (mas) at K-band (λ_0 = 2.2 μm). The KI is developed by the Jet Propulsion Laboratory (JPL), the William M. Keck Observatory (WMKO) and the Michelson Science Center (MSC) and operated by WMKO and the MSC. The KI operates in three modes: (a) measurements of visibility amplitude in the near-infrared (H[1.65 μm] or K[2.1 μm] bands), a.k.a. V^2 mode, (b) N[10 μm] band Nulling (currently in commissioning and shared-risk science period, see Colavita et al.[1] and Serabyn et al.[2]) and (c) Differential Phase between K and L[3.4 μm] bands (currently in development, see Vasisht et al.[3]). For a general update on the KI see the review by Wizinowich et al.[4].

First fringes with KI were obtained in 2001, and commissioning and shared risk science for the V^2 mode took place between June 2002 and April 2004. Since then, it has been open for science proposals from the astronomical community; for information on how to propose, see the MSC web pages at *http://msc.caltech.edu*. Successful KI proposers are granted fully supported service observing.

Shortly after the KI V^2 data are obtained (within hours) it is made available to Principal Investigators via a web-accessible database developed and hosted at the MSC (follow the appropriate links from the home URL above). The data become public after a proprietary period of one year, and accessible to public users after self-registration on that same database. To date, data from 38 nights containing over 50 objects have become publicly accessible.

The KI utilizes adaptive optics wavefront correction, tip-tilt correction (R[0.66 μm] and J[1.25 μm] band sensing, respectively) and a fringe tracker operating in H or K-band which also provides the science data. The sensitivity limits are seeing dependent but approximately as follows: R < 11, J < 10.5 and K < 9.2. Typical calibration accuracy is 5% in V^2 (i.e., statistical plus systematic error $\sigma_V{}^2 = 0.05$).

2. RECENT SCIENCE HIGHLIGHTS

The KI/V^2 has been used for a wide variety of astrophysical studies, including most notably extra-galactic observations[5], spatially resolving the location of the hottest dust in circumstellar disks around young stars, mass determination for pre-main sequence stars in binary systems, testing the paradigm of dust production in Wolf-Rayet stars, and determination of fundamental stellar properties using eclipsing binaries. In this review, we highlight recent results obtained since the SPIE Glasgow conference in 2004[6]. To date, published results from the KI have resulted from time allocated by NASA, Caltech, and U. C. Berkeley.

2.1 Young Stars and their Circumstellar Disks

Spatially resolving the near-infrared emission in young star+disk systems with sub-Astronomical Unit resolution has been among the most productive astrophysics applications of long baseline interferometry, and the same continues to be the case for the KI in its first years of operation. Early observations at the IOTA and PTI as well as using the related technique of aperture masking at the Keck telescope established that essentially all young stellar objects (YSOs) have characteristic near-infrared sizes much larger than expected from then-favored disk models developed primarily to fit the spectral energy distributions. These results have motivated in part the development of a new class of models, that now incorporate realistic physics for the dust disk inner edge. For these and other advances in YSO science using infrared interferometry, and a complete set of references, the reader is referred to the review by Millan-Gabet et al[7].

One way to summarize the basic insight gained from measuring the characteristic near-infrared sizes of YSOs is given in Figure 1, where they are plotted against the luminosity of the central star (including accretion luminosity). This "size-luminosity diagram" lends support to the revised disk models, schematically represented to the right of the figure. The size-L diagram shown contains all data obtained to date at multiple facilities, and the KI contributes the largest sample, 17/31 objects. The KI sample includes intermediate-mass or **Herbig Ae/Be** objects (Monnier et al.[8]) as well as solar-type or **T Tauri** objects (Colavita et al.[9], Eisner et al.[10], Akeson et al.[11], Patience et al.[12]).

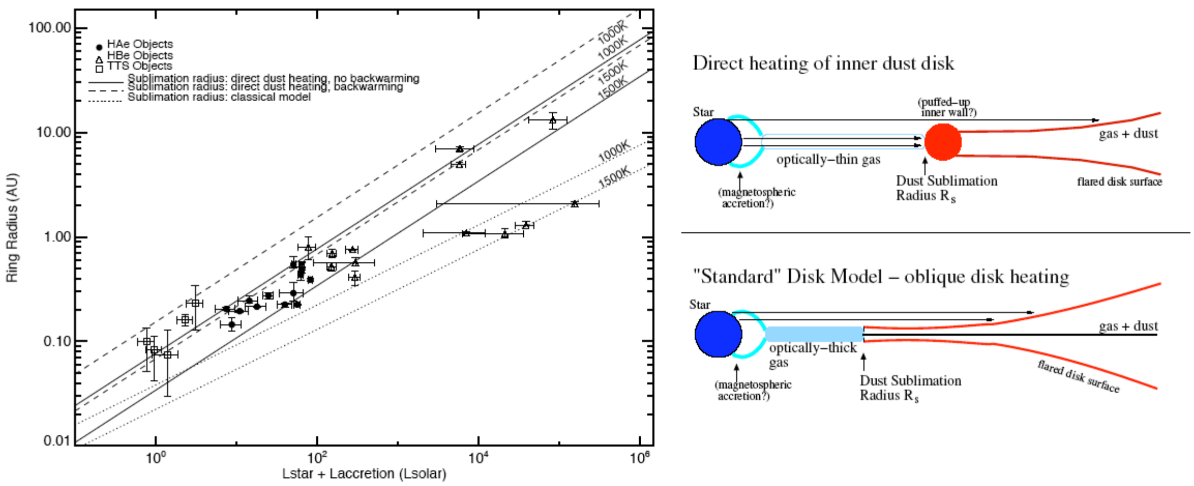

Fig. 1. The "size-luminosity diagram" for the excess near-infrared emission thought to arise at the inner dust edge of circumstellar disks, including data obtained at the KI. The KI has provided observations of a relatively large sample of Herbig Ae/Be and T Tauri objects, providing a sample of uniform data quality for comparison to state-of-the-art models, and extending previous surveys to fainter objects.

Observations at the KI-V^2 have also resolved the infrared emission in an interesting sub-class of YSOs, the **FU Orionis** objects (Millan-Gabet et al.[14]), believed to be young stars surrounded by disks undergoing an episode (possibly recurrent) of highly enhanced accretion activity (triggered by a yet to be identified mechanism). Because the disk emission dominates in these systems, they are promising for putting accretion disk theories to the test (for example, Malbet et al.[15] were able to derive very precise disk parameters for the prototype of the class, FU Ori itself). The FU Ori objects observed at KI however were more resolved than expected from simple power-law disk models. Perhaps the disk paradigm needs to be revised for at least some FU Orionis objects as well, or, alternatively, material in an envelope remnant from the star formation process scatters near-infrared photons and makes these objects appear larger than if thermal disk emission were the only emission mechanism involved.

Essentially all YSO studies to date have focused (for sensitivity reasons) on relatively *young* circumstellar disks. First steps toward understanding the physical conditions in older disks were made by Eisner et al.[16], in observations that spatially resolved the small amounts of dust present inside the (perhaps planet-carved) 4-AU hole in the disk around the **transition object** TW Hya (about 10 Myr of age). These authors find that the inner radius of the optically thin dust is significantly smaller than the expected dust sublimation radius, perhaps suggesting a different truncation mechanism, such as magnetospheric accretion. Fitting the KI visibilities together with the infrared fluxes also requires a population of small dust grains. However, in this environment such small grains would have survival times against radiation pressure much smaller (about 1 yr) than the age of the system, suggesting that they are replenished, perhaps by collisions among larger bodies.

2.2 Pre-Main Sequence Star Masses

Measurements of stellar masses, by establishing the physical orbits of stars in multiple systems, allow to place them in observational HR-diagrams and enable tests of models of stellar structure and evolution. Optical interferometers such as the KI can spatially resolve the close binaries and determine their apparent orbits, most notably the inclinations. In combination with radial velocity measurements using Doppler spectroscopy, the physical orbit can be established, and the masses and luminosities of the individual stars obtained. In order to test state-of-the-art models for pre-main sequence stars, accuracies of 10% or better in the masses or better are required.

Boden et al.[17] performed the first PMS stellar mass measurements, using the KI to resolve the apparent orbit of the system HD 98800-B (a double-lined pair in a quadruple system). In combination with astrometry from the Fine Guidance Sensors aboard the Hubble Space telescope and with radial velocity measurements, a preliminary KI orbit (see Figure 2) allowed the individual (sub-solar) masses to be determined with 8% accuracy. When these two stars are placed in the HR-diagram, it becomes apparent that their location does not agree with predictions from stellar models. The disagreement is made smaller by allowing their abundances to be somewhat sub-solar. More stringent tests of competing stellar models will follow as the orbital phase coverage and thus the accuracy in the determination of the fundamental stellar parameters improves. Moreover, the HD 98800-B pair requires a small amount of extinction not present in the HD 98800-A pair, possibly due to obscuration by material in a circumbinary disk around the B pair.

A number of other PMS orbits are being measured at KI (e.g., Haro 1-14c, Schaefer et al.[18]) and can be expected to yield similarly exciting results as the measurements begin to cover significant portions of the orbital periods.

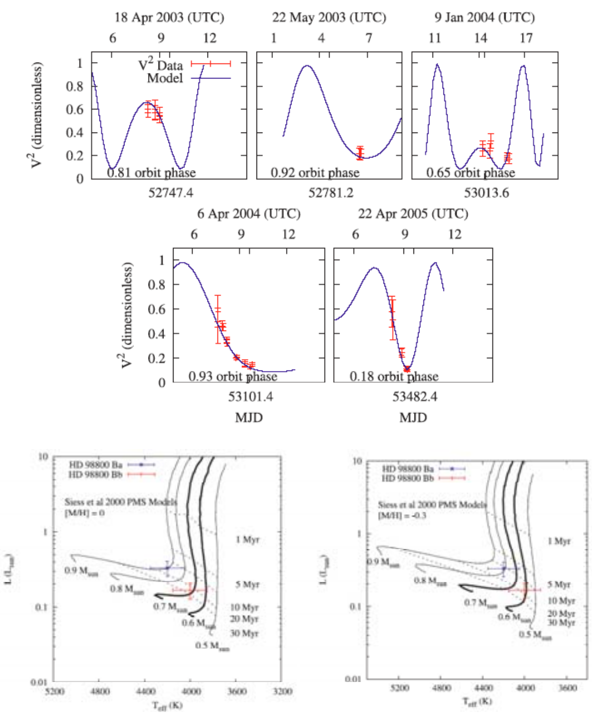

Fig. 2. KI data on the spectroscopic binary HD 98800-B (top panels) and preliminary location of the component stars in the HR-diagram (bottom panel), from Boden et al.[17] The evolutionary tracks corresponding to the masses derived are emphasized with bold lines. Assuming sub-solar abundances, the agreement with the models is only marginal. Reduced data error bars from an improved orbit will permit stringent tests of competing stellar models.

2.3 Wolf-Rayet Stars

Wolf-Rayet stars are evolved massive stars exhibiting powerful winds and mass loss. A small fraction of these objects are also strong infrared sources, indicating the presence of shells of warm dust (carbon rich, or WC-type). For two WC Wolf-Rayet stars, near-infrared images obtained using high spatial resolution single-telescope techniques (i.e. aperture masking, Tuthill et al.[19], Monnier et al.[20]) revealed spiral structures that indicated dust production in the wind-wind interaction of an underlying binary. Observations at the KI aim to spatially resolve these close binaries, in order to better understand the dust production mechanism. Preliminary results from a sample of five objects (Rajagopal et al.[21]) clearly resolve the binaries for two WC objects (WR 140 and WR 137), providing for the latter object the first definite evidence for binarity.

2.4 The RS Oph Nova

Recurrent Novae are very rare, and one such object, RS Oph, underwent an outburst (its 6th since 1898) on 12 Feb 2006. The event prompted a coordinated observing campaign using the IOTA, PTI and KI. Novae are believed to undergo their outbursts when accretion onto a white dwarf from a stellar companion becomes unstable to H-burning. RS Oph is particularly interesting in that the white dwarf mass is within 1% of exploding into a supernova SNIa! The principal result from the interferometer observations made to date (Monnier et al.[22]) is that the near-infrared size of RS Oph (3.2 mas) has not changed significantly from day 4 to day 65 after the outburst. This observation rules out favored models in which the near-infrared emission arises in an expanding shell of hot gas (expected to grow at a rate of 1 mas/day, at the generally accepted distance of 1.6 Kpc). Further, both the shape of the visibility amplitude curve and the non-zero closure phases measured at IOTA indicate an asymmetric brightness. A recent theory proposes instead that the near-infrared emission arises in the modified photosphere of the white dwarf (which effectively becomes a red giant too). Moreover, this scenario favors a closer distance (about 540 pc), such that the binary becomes resolvable, and the interferometer data are indeed consistent with this scenario. If instead the larger distance is confirmed, the authors hypothesize the discovery of a new quasi-stationary, circumbinary, hot gas component (5.1 AU in size). More data from the on-going campaign is expected to definitely confirm or rule out the binary explanation for the resolved near-infrared emission.

3. CONCLUSIONS

The KI in V^2 mode is operating routinely, open for proposals and producing important results in a variety of astrophysics fields. The project continues to improve its performance in a variety of areas (see Wizinowich et al.[4] for details) : sensitivity of the adaptive optics sub-system, sensitivity of the near-infrared science (primarily via real time tracking and local seeing improvements), increased spectral resolution (for example to probe the *gas* component in YSO disks, winds and jets), a V^2 capability at N[10 μm] band, a V^2 capability at L[3 μm] band, and a proposed capability to perform phase referencing and laser-guide-star AO (for example for astrometry studies to measure general relativity effects around the Galactic black hole).

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