Differential phase mode with the Keck Interferometer[1]

Rachel Akeson[2] and Mark Swain[3]

Abstract. We describe the differential phase mode of the Keck Interferometer. The scientific goal of this mode is the **direct detection** and **spectroscopic characterization** of hot, **Jupiter mass planets.** We describe the differential phase effect, the basic observational mode, and the expected differential phase signatures for the **extrasolar planets** discovered through radial velocity searches.

1. Introduction

Direct detection of extrasolar planets is challenging due to the high intensity contrast and small angular separation between the planet and the star. For example, the planet/stellar thermal flux ratio of a Jupiter-size planet orbiting 0.05 pc from a solar-type star is $\sim 10^{-8}$ in the optical. In the infrared, this ratio becomes more tractable; the same planet has a flux ratio of $\sim 10^{-4}$ at 2 μm. While the planet alone could be detected at this level, the nearby star makes this detection a problem of intensity dynamic range and spatial resolution. At a distance of 20 pc, the angular separation of this planetary companion is 2.5 milliarcseconds, smaller than the diffraction limit of a single Keck 10-m telescope. Interferometric techniques can provide both the necessary sensitivity and resolution to study extrasolar planets in the infrared.

2. The Keck Interferometer

The Keck Interferometer project will connect the two 10-m Keck telescopes and add four 1.8-m outrigger telescopes for imaging and astrometry. This NASA-funded project has three Key Science areas:

- Detection of exo-zodiacal emission around nearby stars (technique = nulling).
- Direct detection of warm, giant planets (technique = differential phase).
- Astrometric detection of Uranus-mass planets to 20 pc.

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[2]IPAC/Caltech, Pasadena CA, 91125

[3]JPL, Caltech, Padadena CA, 91109

3. How the Interferometer Works

In the interferometer, the light is collected by two telescopes and the optical paths are matched using a delay line to see the fringe. The light is combined from each telescope with a beam splitter and the combined light is measured with a detector. As the delay line moves away from the exact pathlength match, the detected intensity is modulated. The fringe amplitude and phase are measured by stroking the delay line over an optical distance of one wavelength and counting the photons in each of four bins, labeled A, B, C, and D. The amplitude squared and phase are then given by

$$V^2 = \frac{\pi}{2} \frac{\langle (A-C)^2 + (B-D)^2 \rangle}{\langle A+B+C+D \rangle^2}$$

$$\phi = \tan^{-1} \frac{B-D}{A-C}.$$

4. Differential phase

In the differential phase mode, the presence of a faint companion is detected by measuring the fringe phase simultaneously at two or more wavelengths. A phase difference as a function of wavelength is produced by two effects:

1. The separation between the two sources as a fraction of a fringe is a function wavelength.
2. For sources with different spectral energy distributions, the source amplitudes will contribute different fractions to the measured fringe at different wavelengths, producing a phase difference.

In the narrow band limit, the fringe from the primary is given by

$$V_p \cos(kx)$$

where k is the wavenumber and x is the delay. The secondary source fringe is given by

$$V_s \cos[k(x+\delta)],$$

where δ is the separation of the two sources on the sky as measured in delay space and is a function of the baseline and ds, the separation on the sky, $\delta = \vec{ds} \cdot \vec{B}$. Both the amplitudes of the fringes V_p and V_s, as well as k will depend on the wavelength band. The relative contribution of the primary and secondary to the photon count for a particular measurement bin, A, B, C, D, is given by

$$A_{\lambda_1} = \int_0^{\lambda_1/4} V_p \cos[k_1 x]\, dx + \int_0^{\lambda_1/4} V_s \cos[k_1(x+\delta)]\, dx$$

and so on. Once the source flux densities and separation vector are specified, the phase at each wavelength and the differential phase can be easily computed from these integrals at each wavelength.

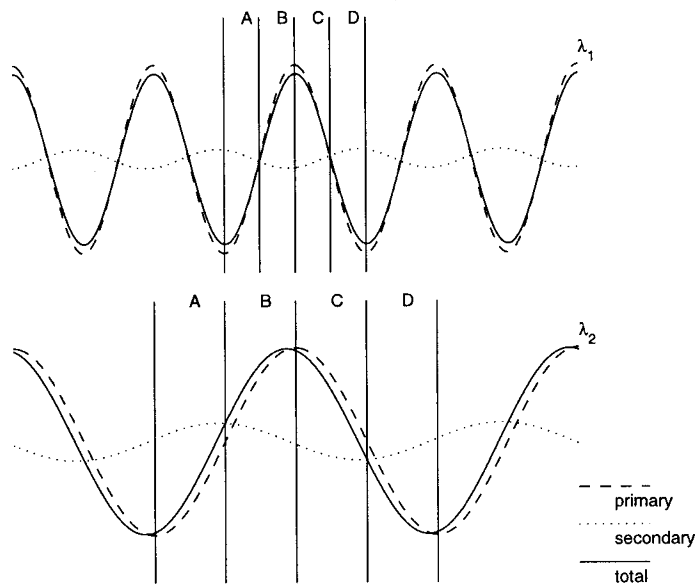

Figure 1. The fringes in delay space for the primary and secondary sources at different wavelengths. The wavelength difference and secondary/primary flux ratio have been exaggerated to show the differential phase.

5. Observational Technique

As the differential phase effect is roughly proportional to the relative source fluxes, it is essential to make very precise phase measurements. The phase sensitivity goal for the differential phase mode at the Keck Interferometer is 0.1 milliradians. One of the two wavelengths will be used as the reference for fringe tracking. The phase at the second wavelength will be measured simultaneously as an offset phase from the reference wavelength. By using the same beam path for the 2 wavelengths and measuring the phases simultaneously, many systematic effects will be removed from the observed differential phase. Differential phase observations with the Keck Interferometer will be possible from H to M bands (1.6 to 5 μm) with currently planned instrumentation and in the N band (10 μm) with potential instrumentation.

One complication for these multi-wavelength observations is the wavelength dependence of the atmospheric dispersion. If this effect is not corrected, the fringe packets at the two wavelengths will not be at the same location in delay space. At the Keck Interferometer an atmospheric dispersion compensator (ADC) will be inserted into the optics path to equalize the phase delay at the two wavelengths.

As the interferometer tracks a source across the sky, the projected baseline will evolve in time. Thus, the differential phase for a given source will be a function of hour angle (see figure). This evolution of the differential phase can be used to distinguish the true signal from instrumental effects.

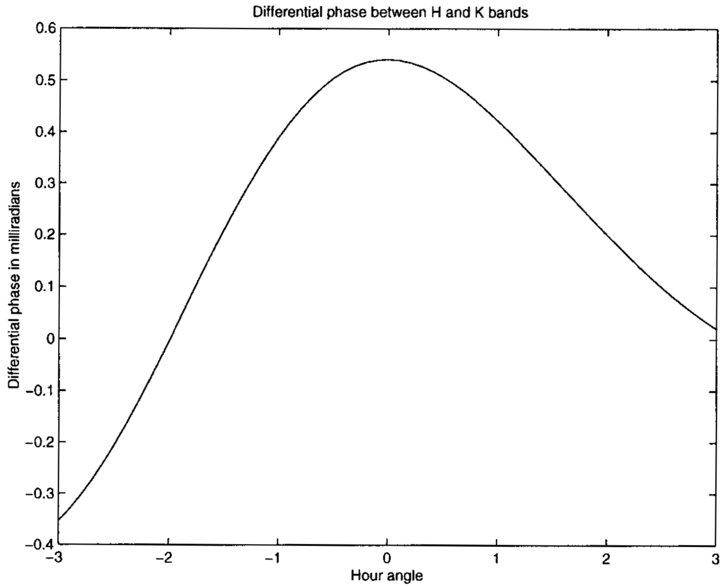

Figure 2. The H–K band (1.6 to 2.2 μm) differential phase as a function of hour angle for a "51 Peg" like planet for the Keck Interferometer baseline. The star–planet separation is 4 milliarcseconds, the star has T_{eff} = 6000 K and the planet has T_{eff} = 1200 K.

As part of the differential phase mode development, an ADC will be installed this summer at the Palomar Testbed Interferometer (PTI). Test observations will be made between the H and K bands on known binary sources.

6. Extrasolar Giant Planets

The companions to nearby stars discovered through radial velocity searches are the best candidates for warm, Jupiter mass planets. As warmer planets will have a higher flux relative to the stellar flux, and therefore a larger differential phase, the planets with orbits smaller than 0.3 AU (listed below) are the best targets for the Keck Interferometer.

If the planet emits as a blackbody (see discussion below), the flux is determined by the planet's effective temperature and radius. In models for brown dwarfs and giant planets, the radius is roughly independent of mass and is $\sim 8 \times 10^9$ cm (1.1 R_J) for planets older than 10^8 years (Saumon et al. 1996; Burrows et al. 1997). The effective temperature of each planet listed above can be calculated given the stellar spectral type and an estimate of the albedo.

The recent observational work on brown dwarfs and extrasolar planets is complemented by theoretical work in modeling the structure and evolution of these objects (see e.g. Saumon et al. 1996, Burrows et al. 1997, Seager & Sasselov 1998). For our calculations, the most important aspect of these studies is the departure from a blackbody spectrum in the near-infrared. Comparing a model spectrum from Burrows et al. (1997) and the corresponding blackbody at T_{eff} = 1100 K (see figure), strong features can be seen in the near-infrared

Star Name	$M sini$ M_J	Period days	Semi-major axis AU	mas	Spectral type	T_* K	T_{planet} K
HD 187123	0.52	3.1	0.042	0.9	G5	5770	1180
τ Boo	3.64	3.3	0.042	2.7	F6	6360	1660
51 Peg	0.44	4.2	0.051	3.3	G2	5850	1200
υ And	0.63	4.6	0.053	3.9	F8	6200	1500
HD 217107	1.28	7.1	0.07	3.5	G8	5570	880
ρ^1 Cnc	0.85	14.6	0.12	9.6	G8	5570	630
Gliese 86	3.6	15.8	0.11	10.1	K1	5080	600
HD 195019	3.43	18.3	0.14	3.7	G3	5830	690
ρ Cor Bor	1.1	39.6	0.23	13.2	G0	6030	460

Table 1. Masses and orbital characteristics of some candidate extra-solar planet systems. This list is taken from G. Marcy's web page. The planet effective temperature is given for an albedo of 0.3. Spectral types are from SIMBAD and the effective temperatures are from Gonzalez (1998).

bands. In the following table the differential phase is estimated for both blackbody spectra and the Burrows et al. models. Reflected light is neglected in these calculations, based on the conclusions of Seager & Sasselov (1998).

T_{eff}	Emission type	Differential phase in milliradians			
		H–K	K–L	L–M	N_1–N_2
1100	Blackbody	0.3	1.4	3.2	7.8
1100	Model	0.6	0.9	1.4	6.9
600	Blackbody	0.001	0.032	0.18	2.0
600	Model	0.018	0.045	0.15	1.6

Table 2. Predicted differential phase for planets emitting as blackbodies and for model planet spectra at 2 temperatures. The fluxes for the model planets are taken from Burrows et al. 1997. The differential phase within the N band is calculated from 10.5 to 12 μm. Recall that the sensitivity goal for the Keck Interferometer is 0.1 milliradians.

By modeling the data obtained from differential phase observations, the flux as a function of wavelength can be derived. This can be used to estimate the following properties of the extrasolar giant planets:

Effective temperature Estimate using the flux in line-free regions of the spectrum and models for the planetary radius.

Spectral features The Keck Interferometer will have roughly 100 spectral channels across the band. Departures from a blackbody spectrum, particularly in the near-infrared could indicate the presence of molecules such as methane.

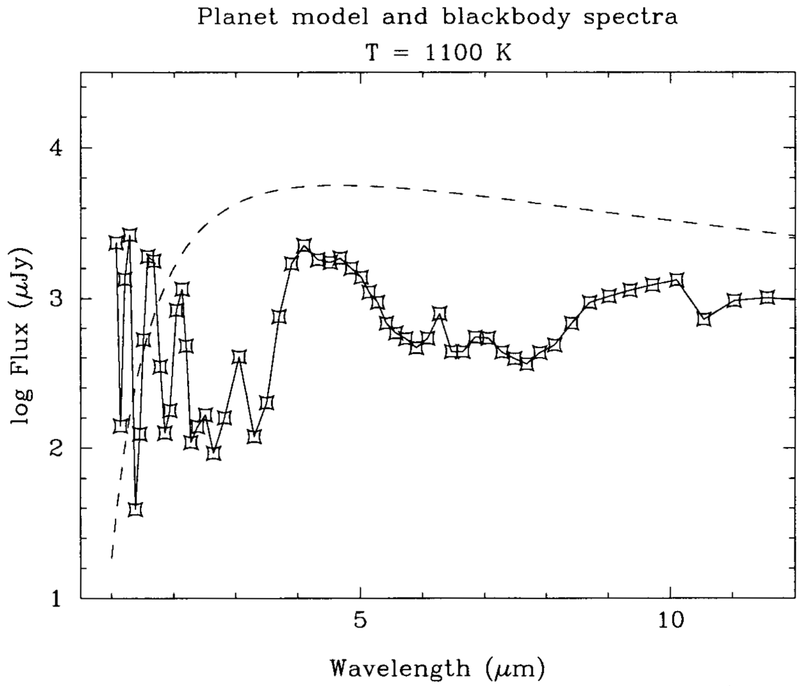

Figure 3. The model spectrum (squares and solid line) for a planet at 10 pc with an effective temperature of 1100 K from Marley (personal communication) and Burrows et al. (1997) and the corresponding blackbody spectrum (dashed line).

Orbital parameters Measuring the differential phase throughout an orbital period will yield the inclination, and thus the true planetary mass.

7. Other targets

The NASA Key Science program will use differential phase to study warm, Jupiter mass planets. There are many other kinds of astronomical sources which can benefit from an observational method which allows study of faint emission near a bright source. This list includes spectroscopic single-line binaries, brown dwarf binary companions, and asymmetries in circumstellar dust shells.

References

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Saumon, D. et al, 1996, ApJ, 460, 993

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