MONET

Transit Follow-ups with MONET-North

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Abstract

MONET is a new network of telescopes at the McDonald Observatory, USA, and at the South African Astronomical Observatory, South Africa. MONET will provide extended follow-up capabilities for planetary transits on both hemispheres and enable automated optical observations at rapid response and long coverage.
We demonstrate the MONET-North performance and its capabilities to allow high precision transit photometry. Several transits of the recently detected exoplanet XO-1b have been observed. New sophisticated transit models are presented. Applied to the data, we derive accurate planetary parameters and yield radius and inclination parameters that account for physical effects in the transit models.

The MONET Project

The Mo*nitoring* Ne*twork of* T*elescopes (MONET)* consists of two robotic observatories. The first, MONET-North, started operations in late 2006 at the McDonald Observatory, Texas USA. Its twin telescope, MONET-South, is currently under construction at the South African Astronomical Observatory (SAAO) in Sutherland, and will go on-sky in May 2008.

MONET is funded by the *Alfred Krupp von Bohlen und Halbach Stiftung* and is jointly operated by the Georg-August University Goettingen, Germany, the McDonald Observatory at the University of Texas, and the SAAO.

Hardware: Each MONET site will be equipped with identical configurations, consisting of

- a dedicated, very fast 1.2 m f/7 Ritchey-Crétien *Halfmann* telescope in alt-az mount with Nasmyth-foci (Bischoff et al. 2006, SPIE, 6270, 62701Q)
- a thermo-electrically cooled high cadence *Spectral Instruments* camera with a $2k \times 2k$ *e2v* CCD, offering a total field of view of $169\,\mathrm{deg}^2$ $(13.5\,\mu\mathrm{m}$ pixel size)
- an *Apogee* Alta E47 $1k \times 1k$ CCD for guiding (which is currently used as the primary CCD until the $2k \times 2k$ are deployed)
- a two-floor double-roofed enclosure with a fully temperature-controlled computer and control cabinet. The clamshell roofs support for rapid slewing and for unperturbed seeing.
- a weather station for continous ambient monitoring
- automatic roof engines, including emergency power supply
- server infrastructure for telescope control, robotic operations, remote interfaces and data storage

Operations can be carried out either completely remotely from the home institutions, or from anywhere by web-interface (including visual control). The robotic sensoring ensures safe operations if conditions allow. Robotic scheduling of observations and data acquisition is under development.

Aims: MONET is designed for follow-up studies of variable objects with high cadence, in particular of

- transiting extrasolar planets
- stellar pulsators
- monitoring of young TTauri stars

Also, 40% of the time is reserved for educational projects and outreach at participating schools worldwide (Hessmann 2007, AN, 328, 681).

Figure 1: MONET-North in its open-roof "barn" at the McDonald Observatory, waiting for a clear sky.

Exoplanetary Transit Light Curve Models

We present synthetic transit light curve models computed from a physical model of the star and the extrasolar planet.

Transits are conventionally modelled from geometric occultations of simple discs, which are available in analytic forms (Mandel & Agol 2002, ApJ, 580L, 171)

Our new approach (*"NEP"*) reflects the physical properties of the system, and implements:

- non-spherical shapes of star and planet (*gravitational brightening*)
- arbitrarily eccentric planetary orbits
- tidally *un*-locked planets and stellar rotation
- consideration of stellar spots
- additional third light from blended objects
- mutual irradiation of the components
- reflection on and heating of the planetary atmosphere
- accurate treatment of stellar *and* planetary limb darkening (PHOENIX, Claret 2000, A&A, 363, 1081)
- sophisticated radiative transport from stellar atmosphere models (PHOENIX, Hauschildt et al. 1999, ApJ, 512, 377)

Application of our *NEP* model light curves to high precision transit observations (COROT, KEPLER) will reveal finer, detailed planetary system properties.
Secondary transits are expected in the data and can be modelled as well as deviations in the light curve shape due to stellar light reflected by the planet.

Light curves for a tidally circularized hot jupiter transiting a solar-like star are shown in Fig. 2, with the following properties:

Parameter	Star	Planet
Mass	$M_* = 1.0\,\mathrm{M}_\odot$	$M_p = 1.047\,\mathrm{M_J}$
Radius	$R_* = 1.0\,\mathrm{R}_\odot$	$R_p = 0.995\,\mathrm{R_J}$
Orbital period		$P = 3.0\,\mathrm{days}$
Inclination		$i = 88.0^\circ$
eff. Temperature.	$T_{\mathrm{eff},*} = 7000\,\mathrm{K}$	$T_{\mathrm{eff,p}} = 350\,\mathrm{K}$
Surface gravity log g	$\log g_* = 4.0$	$\log g_p = 3.5$

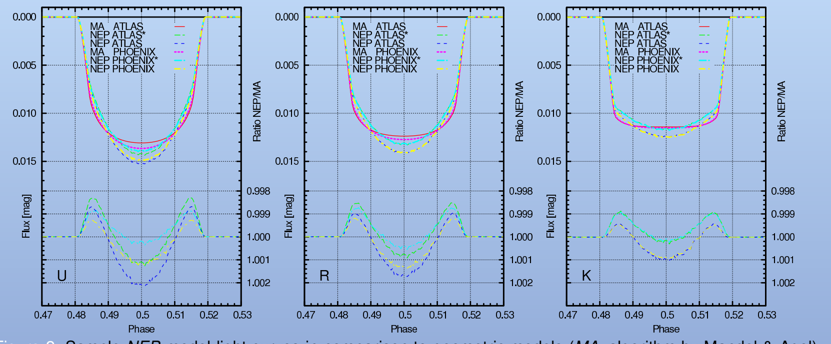


Figure 2: Sample *NEP* model light curves in comparison to geometric models (*MA*, algorithm by Mandel & Agol). Light curves (*top*) are computed in pairs of identical (quadratic) limb darkening coefficients (either from the ATLAS or PHOENIX catalog), for different filters (*U, R, K*). Limb darkening is stronger at bluer than at redder wavelengths, and hence the transit bottom shows a more convex or flatter shape, respectively. The model ratios (*bottom*) of mutual pairs exhibit systematic differences between the physical and the geometric algorithms. The deviations caused by physical effects are of order 0.2% in *U*, and 0.1% in *K*, and are to be systematically checked on apropriate data. Note the large effect due to the choice of limb darkening catalog alone (the starred curves apply additional flux interpolation).

Modelling MONET Transit Follow-ups

We present photometric observations (R band, Fig. 3) of the extrasolar planetary system XO-1. The transit light curve illustrates the MONET capabilities to produce high precision light curves at the 1% level.

XO-1 b is a hot jupiter that transits in front of its solar-like G1 V host star of 11$^{\mathrm{th}}$ magnitude.

System parameters: stellar radius and mass $R_* = 0.928^{+0.018}_{-0.013}\,\mathrm{R}_\odot$, $M_* = 1.00 \pm 0.03\,\mathrm{M}_\odot$; effective stellar temperature $T_{\mathrm{eff}} = 5750\,\mathrm{K}$; planetary mass $M_p = 0.90 \pm 0.07\,\mathrm{M_{jup}}$, planetary orbital period $P = 3.941534\,$days; (McCullough et al. 2006, ApJ, 648, 1228; Holman et al. 2006, ApJ, 652, 1715)

Data Reduction includes dark correction, sky flat fielding, background-, extinction-, and color correction; and relative aperture photometry.

Transit modelling is performed by fitting synthetic *NEP* light curve models to the 1307 data points, with planetary radius R_p, orbital inclination i and transit timing T_c as free parameters.

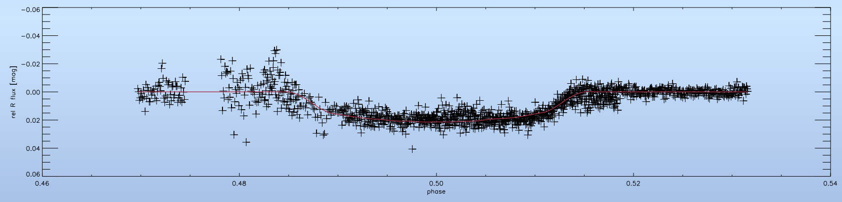


Figure 3: Folded transit light curves of XO-1 b, observed with MONET-North over two consecutive transits in *R*, and best-fit transit model light curve.

Figure 4 (⟶): Probability distribution for model parameters R_p and i, based on least squares minimizations. Contours of confidence levels are plotted, the best-fit model with 1σ errors is labelled with a cross.

Results from least-squares minimizations yield planetary radius and orbital inclination (Seemann 2008, in prep.):

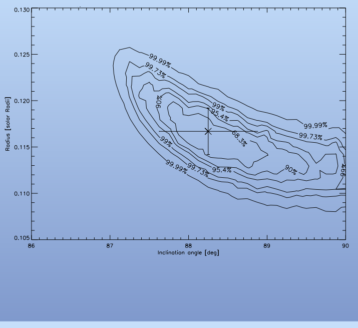
Parameter	Value[a]
Radius	$R_p = 0.1167 \pm 0.0013\,\mathrm{R}_\odot$
	$= 1.1611 \pm 0.0124\,\mathrm{R_J}$
Inclination	$i = 88^\circ.25 \pm 0^\circ.38$

[a] for quadratic limb darkening (PHOENIX)

Values agree with those of McCullough et al. ($R_p = 1.2064 \pm 0.052\,\mathrm{R_J},\ i = 87^\circ.7 \pm 1^\circ.2$; scaled to the same $R_* = 0.928^{+0.018}_{-0.013}$ as applied here). Revised estimates by Holman et al. are within agreement in radius ($R_p = 1.184^{+0.028}_{-0.018}$). Our values slightly differ (Fig. 4) in inclination ($i = 89^\circ.31^{+0.46}_{-0.53}$), reflecting a model deviation attributed to physical effects of the same magnitude as in Fig. 2.

The Data shows the MONET capabilities of producing accurate light curves.

***NEP* Models** present solutions with systematic differences to geometric models. The deviations in the results for the MONET data are consistent with results obtained when fitting our models to the data of Holman et al. The exact correlation between the systematics and the modelled physical effects is to be investigated on high quality data.



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