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First Results from the MIT Optical Rapid Imaging System (MORIS) on the IRTF: A Stellar Occultation by Pluto and a Transit by Exoplanet XO-2b

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ABSTRACT. We present a high-speed, visible-wavelength imaging instrument: MORIS (the MIT Optical Rapid Imaging System). MORIS is mounted on the 3 m Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. Its primary component is an Andor iXon camera, a nearly 60” square field of view with high quantum efficiency, low read noise, low dark current, and full-frame readout rates ranging from as slow as desired to a maximum of between 3.5 Hz and 35 Hz (depending on the mode: read noise of 6 e− pixel−1 and 49 e− pixel−1 with electron-multiplying gain = 1, respectively). User-selectable binning and subframing can increase the cadence to a few hundred hertz. An electron-multiplying mode can be employed for photon counting, effectively reducing the read noise to subelectron levels at the expense of dynamic range. Data cubes, or individual frames, can be triggered to several-nanosecond accuracy using the Global Positioning System. MORIS is mounted on the side-facing exit window of SpeX, allowing simultaneous near-infrared and visible observations. Here, we describe the components, setup, and measured characteristics of MORIS. We also report results from the first science observations: the 2008 June 24 stellar occultation by Pluto and an extrasolar planetary transit by XO-2b. The Pluto occultation of a 15.8R magnitude star has a signal-to-noise ratio of 35 per atmospheric scale height and a midtime error of 0.32 s. The XO-2b transit reaches photometric precision of 0.5 mmag in 2 minutes and has a midtime timing precision of 23 s.

1. INTRODUCTION

The observational frontier of astronomy has been expanded by the capability for increasingly shorter and more accurate time resolution. Technological advances in many areas have contributed to the efficacy of high-speed instrumentation: frame-transfer charge-coupled devices (CCDs) with effectively no dead time, high quantum efficiency, and low read noise; increased computational data-streaming speeds and storage capacities; and portable, affordable access to the Global Positioning System (GPS). Subsecond observations have revealed new information about pulsars, cataclysmic variables, X-ray binaries, stellar pulsations (e.g., Phelan et al. 2008; Buckley et al. 2010), and bodies in the solar system through the observation of stellar occultations (e.g., Elliot 1979; Elliot & Olkin 1996).

In particular, subsecond resolution of occultations by bodies in the outer solar system probe these objects at the highest spatial resolution that can be achieved by any Earth-based method (i.e., a few kilometers at 30 AU; Gulbis et al. 2006; Person et al. 2006). Recent observations of stellar occultations by Pluto indicate that its atmosphere has halted its expansion (Young et al. 2006; Elliot et al. 2007) and reveal dynamical features such as high-altitude waves (McCarthy et al. 2008; Person et al. 2008). Continued monitoring via occultation observations is necessary to assess atmospheric changes as Pluto moves away from peri-helion and before the arrival of NASA’s New Horizons spacecraft in 2015.

A similar technique has been used to discover and characterize planets outside of the solar system: observing the fractional change in light as an exoplanet transits in front of its parent star. Although only a subset of exoplanets are geometrically positioned for these events to be viewed from Earth, there are now over 100 known transiting exoplanets.7 High-quality photometry and accurate timing of exoplanet transits provide information on the planet’s mass, the ratio between the planetary and stellar radius, the semimajor axis of the planet, and stellar limb-darkening parameters and can reveal transit timing variations that may be due to additional planets or satellites.

7 See the Extrasolar Planets Catalog at http://exoplanet.eu/catalog.php for the most recent count.
Here, we present a new optical, high time resolution instrument called MORIS (the MIT Optical Rapid Imaging System) and its first science observations of a stellar occultation and an exoplanet transit. MORIS is located on NASA’s 3 m Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. It is mounted on the side-facing exit window of SpeX, a 0.8–5.4 μm spectrograph and imager (Rayner et al. 2003). This mounting allows for simultaneous high-speed observations at visible wavelengths (using MORIS) and in the near-IR (using SpeX).

In § 2, the instrument and its components are described in detail. Section 3 contains results from a single-chord observation of a stellar occultation by Pluto on 2008 June 24 and a transit by exoplanet XO-2b on 2008 December 6. A summary and future work are presented in § 4.

2. INSTRUMENT SPECIFICATIONS

MORIS is based on the Portable Occultation, Eclipse, and Transit System (POETS: Souza et al. 2006; Gulbis et al. 2008). POETS were developed to allow high-quality, high-speed, GPS-timed, optical observations in an easy-to-transport format. MORIS has a similar design to POETS; however, it is optimized to interface with SpeX and is permanently based at the IRTF. The primary instrument components are described in detail next. A schematic of the instrument setup is shown in Figure 1, and a summary of the instrument characteristics is provided in Table 1.

2.1 Camera

The backbone of the system is an Andor iXon® EM+ DU-897 camera. This is a frame-transfer, high-quantum-efficiency, low-read-noise camera. A unique aspect of this camera is the selection of either conventional readout or electron multiplying (EM) via an extended serial register prior to readout. In EM mode, transferred electrons undergo impact ionization, strengthening the observed signal without increasing read noise. This process effectively reduces read noise to subelectron levels. The output of either the conventional or EM register is routed to a preamplifier stage at which one of three gain settings is selected (1×, 2.4×, or 5×). The signal is then fed to one of two analog-to-digital converters (ADCs): a 16-bit ADC with readout rate of 1 MHz or a 14-bit ADC with readout rates of 3, 5, or 10 MHz. The 1 and 3 MHz rates are available in conventional mode and all rates function in EM mode. Each mode, preamp setting, and readout rate has different performance characteristics. See Table 2 for read noise and gain measurements.

A measurement of the linearity of the detector is shown in Figure 2. We find that for the three tested modes (two conventional and one EM), the linearity conforms to the manufacturer’s specification. Linearity measurements for three different camera modes are provided in Fig. 2.

![Diagram of the MORIS setup](Image)

**Fig. 1.**—Schematic drawing of the MORIS setup. The “cool rack” refers to one of four thermally isolated cabinets around the perimeter of the IRTF Multi-

### Table 1

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final beam speed</td>
<td>f/12.7</td>
</tr>
<tr>
<td>CCD</td>
<td>E2V CCD97; 512×512, 16 μm² pixels</td>
</tr>
<tr>
<td>Full-well capacity</td>
<td>158, 268 e⁻</td>
</tr>
<tr>
<td>Linearity</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Plate scale</td>
<td>0.1139° pixel⁻¹</td>
</tr>
<tr>
<td>Field of view</td>
<td>58.3”×58.3”</td>
</tr>
<tr>
<td>Readout rate</td>
<td>3.5 frames s⁻¹ (full frame, 1 MHz amplifier); 35 frames s⁻¹ (full frame, 10 MHz amplifier); up to hundreds of frames per second with binning and/or subframing</td>
</tr>
<tr>
<td>Dead time</td>
<td>1.7 ms (for 512 rows at the default vertical shift speed)</td>
</tr>
<tr>
<td>Dark current</td>
<td>&lt;0.001 e⁻ pixel⁻¹ s⁻¹</td>
</tr>
<tr>
<td>GPS accuracy</td>
<td>&lt;1 μs</td>
</tr>
<tr>
<td>GPS antenna cable delay</td>
<td>77 ns⁻¹</td>
</tr>
<tr>
<td>GPS trigger cable delay</td>
<td>30.8 ns⁻¹</td>
</tr>
<tr>
<td>Current filters</td>
<td>SDSS g’, r’, i’, and z’; Johnson V; V; r; OG590 (long-pass red)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic</td>
<td>Value</td>
</tr>
<tr>
<td>Cool rack</td>
<td></td>
</tr>
<tr>
<td><strong>Table 1</strong></td>
<td></td>
</tr>
<tr>
<td><strong>SUMMARY OF INSTRUMENT CHARACTERISTICS</strong></td>
<td></td>
</tr>
</tbody>
</table>

- Saturation signal per pixel and linearity up to saturation (as a percentage variation from a straight-line fit) provided by the manufacturer. Linearity measurements for three different camera modes are provided in Fig. 2.

- Plate scale was measured from astrometric fits using stars from the UCAC2 catalog to images of open cluster Berkeley 81.

- Dark current is negligible in exposures up to 240 s at -70°C. This value represents the manufacturer’s specification.

- Based on a manufacturer-specified time delay of 1.54 ns ft⁻¹, for 50 ft of RG-58 and 20 ft of RG-174 coaxial cable.
These can be directed into the MORIS optical path. The beam at either 0.8 μm or 0.95 μm—wavelengths shorter than these can be directed into the MORIS optical path. The beam exiting from SpeX is f/38. To speed up the beam and allow stronger signal over shorter time, we chose a focal reduction of 3:1. There is a constraint on the distance that the instrument can extend from the side of SpeX to allow adequate clearance for instrument swapping at the IRTF Cassegrain focus. Thus, a folding mirror is required to direct the beam downward. The path was also designed to minimize the number of optics in order to prevent loss of light. A schematic of the resulting optical path is shown in Figure 3. This three-lens, one-mirror design was created using the ZEMAX optical design program from Focus Software, Inc.

The three lenses are custom-made; the first and third are from Schott SF5 and the second is from Schott BK7. All lenses are antireflectance coated with a single layer of MgF₂ at 590 nm to a level of less than 3.5% reflectance over visible wavelengths. The mirror is coated with protected silver, allowing greater than 90% reflectivity over visible wavelengths. The fused-silica camera window has a standard Andor antireflectance coating, with reflectance of roughly 4% over visible wavelengths.

TABLE 2
MEASURED READ NOISE AND GAIN

<table>
<thead>
<tr>
<th></th>
<th>Read noise (e⁻)</th>
<th>Gain (e⁻ ADU⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1x</td>
<td>2.4x</td>
</tr>
<tr>
<td>Conventional Mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 MHz</td>
<td>8.58</td>
<td>6.35</td>
</tr>
<tr>
<td>3 MHz</td>
<td>13.56</td>
<td>10.04</td>
</tr>
<tr>
<td>EM Mode (EM = 20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 MHz</td>
<td>8.98</td>
<td>5.49</td>
</tr>
<tr>
<td>3 MHz</td>
<td>12.37</td>
<td>7.49</td>
</tr>
<tr>
<td>5 MHz</td>
<td>11.68</td>
<td>7.33</td>
</tr>
<tr>
<td>10 MHz</td>
<td>12.33</td>
<td>7.70</td>
</tr>
<tr>
<td>EM Mode (EM = 40)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 MHz</td>
<td>0.56</td>
<td>0.36</td>
</tr>
<tr>
<td>3 MHz</td>
<td>0.78</td>
<td>0.47</td>
</tr>
<tr>
<td>5 MHz</td>
<td>1.05</td>
<td>0.66</td>
</tr>
<tr>
<td>10 MHz</td>
<td>1.10</td>
<td>0.70</td>
</tr>
<tr>
<td>EM Mode (EM = 100)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 MHz</td>
<td>0.42</td>
<td>0.26</td>
</tr>
<tr>
<td>10 MHz</td>
<td>0.45</td>
<td>0.28</td>
</tr>
</tbody>
</table>

* Amplifier for these modes is 16 bit. All other modes are 14 bit.
* Effective read noise and gain values are the mean of multiple measurements with the camera air-cooled to -70°C.
* Values at a higher EM setting are given only for 5 MHz and 10 MHz amplifiers to demonstrate subelectron read noise for all gain settings.

2.2 Fore Optics Box

SpeX has two CaF₂ dichroic beam splitters, which cut the beam at either 0.8 μm or 0.95 μm—wavelengths shorter than these can be directed into the MORIS optical path. The beam...
To derive the response of the system, we consider the CCD quantum efficiency and the throughputs of the components in the fore optics box, as described previously. We combine these values with the throughputs of the primary mirror, secondary mirror, SpeX dichroic, and two SpeX windows with single-layer CaF\(_2\) coating (efficiencies given in Table 4 of Rayner et al. 1993). The total MORIS detector response for each dichroic is shown in Figure 4a.

There is a custom-made filter wheel that holds 10 (1 inch diameter) filters. The wheel is rotated by an Animatics Smart-Motor SM2330D, and a positive mechanical detent locking system is employed to ensure positioning repeatability to better than 15 \(\mu\)m. The current suite of 5 mm thick filters was made by Asahi Spectra: SDSS \(g', r', i', \text{ and } z'\) (following the Sloan Digital Sky Survey; Fukugita et al. 1996); Johnson \(V; VR\) (following Jewitt et al. 1996); and OG590 (a long-pass red filter comprised of 3 mm Schott OG590 and 2 mm BK7). The detector response, including the transmission curves of the filters, is plotted in Figures 4b and 4c. ZEMAX simulations show that there should be a negligible change in focus between the different filters or an open position.

We designed a light-tight box to interface with SpeX, house the optics and filter wheel, and allow mounting and focusing of the camera. The anodized components of the fore optics box were machined at MIT to a positional accuracy of better than 0.005 inches. Figure 5 is a photograph of this box mounted onto the side of SpeX.

Fig. 3.—ZEMAX diagram of the MORIS optical path, from the exit window of SpeX to the Andor Ixon camera window. The 3:1 reducing optics consist of three lenses and one folding mirror.

Fig. 4.—The MORIS detector response as a function of wavelength. The response is shown as a percentage of light entering the telescope and thus includes throughput from all optics, as well as CCD quantum efficiency. (a) Response with no filter. The two curves correspond to the SpeX 0.8 \(\mu\)m and 0.95 \(\mu\)m dichroic beam splitters, one of which must be selected to direct light out of the side-facing exit window and into the MORIS fore optics box. (b) Response for the Sloan filters, with the 0.95 \(\mu\)m dichroic. Sloan \(g', r', i', \text{ and } z'\) are represented by dotted, gray, black, and dashed lines, respectively. (c) Response for the remaining filters, with the 0.95 \(\mu\)m dichroic. Johnson \(V, VR\), and long-pass red (OG590) are represented by thick black, dot-dashed, and thick gray lines, respectively.

2.3 Timing

To ensure accurate timing, we use a Spectrum Instruments, Inc., Intelligent Reference/TM-4 GPS. A small weatherproof antenna has been attached to the top of the telescope with an
3. SCIENCE OBSERVATIONS

3.1 Stellar Occultation of P571 by Pluto

MORIS was mounted on the IRTF in 2008 May. Our first observing run was on the night of June 23/24 to view the predicted stellar occultation of P571 (USNO-B 0729-0691269; $R$ magnitude 15.8) by Pluto (McDonald & Elliot 2000). The refined occultation prediction was based on nearly 50 astrometric observations of the star and more than 300 astrometric observations of Pluto; the measured star position showed an offset of nearly $+0.4''$ in right ascension and $-0.2''$ in declination from the catalog position: $R.A. = 17:58:22.3951$ and decl. = $-17:02:49.347$ at the epoch of the event. The predicted shadow path had a centerline $120 \pm 443$ km North of Mauna Kea, and the predicted midtime for the occultation from the IRTF was 2008 June 24 10:35 : 53 ± 00:00:10 UT. The IRTF was the only site from which we arranged to observe the occultation.

The observations were carried out using the IRTF’s remote observing option, which was economical given that we were awarded only 4 hr of telescope time to observe the event. The occultation data cube spanned 40 minutes, centered on the predicted midtime. Each frame was triggered from the GPS at a cadence of 4 Hz. The camera settings were 1 MHz conventional mode, with $2.4 \times$ preamplifier gain. We used the SpeX $0.95 \mu m$ dichroic with no filter. Binning was set to $2 \times 2$, providing an effective pixel size of $0.23''$. There were thin clouds throughout the observations, the air mass ranged from 1.25 to 1.45, and the seeing was approximately 0.7 to 1.0''.

Simultaneous observations were started using SpeX with Guidedog (Rayner et al. 2003); however, Guidedog crashed 10 minutes before the predicted midtime and could not be restarted in time to observe the occultation.

Careful data reduction was required for this event because of the variable clouds. In addition, the MORIS field of view was vignette at the corners and contained significant scattered light (Fig. 6; see § 4 for additional discussion). We performed
aperture photometry on each frame to extract the combined signal from Pluto, Charon, and P571. This procedure was repeated for two comparison stars in the frame that were slightly brighter than P571. Background regions were carefully selected around each aperture in order to accurately subtract out background light. To calibrate the light curve, we used data taken before and after the occultation when Pluto and the star were well separated. We find the background fraction, \((\text{Pluto+Charon})/(\text{Pluto+Charon+P571})\), to be \(0.826 \pm 0.001\). The highest signal-to-noise ratio (S/N) for the unocculted Pluto, Charon, and P571 baseline was obtained using raw data, with an aperture having a diameter equal to 12 superpixels, and dividing by the mean of the signal from the two comparison stars. The calibrated light curve shown in Figure 7 has a S/N of 35 per atmospheric scale height of 60 km on Pluto.

A geometric solution was not possible, since we have only a single chord for this occultation. In addition, extensive attempts to derive object positions using multiple point-spread-function fitting did not return accurate results. A significantly larger number of astrometric frames, extending further before and after the event, would be required for that analysis.

Following Elliot & Young (1992), we fit the light curve by assuming a power-law thermal structure. We assumed the best-fit atmospheric parameters from Elliot et al. (2007) of half-light radius \(r_H = 1276.1\) km, equivalent isothermal gravitational to thermal energy ratio at half-light radius \(\lambda_{\text{iso}} = 18.3\), and thermal gradient parameter \(b = -2.2\). A one-limb model was used, and the surface radius was set to a low enough value such that it would not effect the light curve. Only data points of flux > 0.4 were used, since Pluto’s lower atmosphere is known to deviate from isothermal (e.g., Elliot et al. 2007; Young et al. 2008, and references therein; Lellouch et al. 2009). Best-fit values were found for closest approach distance (99.9 ± 99.9 km), midtime (1143.80 ± 0.32 s from the data cube start time of 10:18:00.00 UT), full-scale unoccultated signal (1.02 ± 0.49), and slope of the full-scale signal (\(-5.49 \times 10^{-6} \pm 3.34 \times 10^{-4}\)). The best-fit model is plotted along with the data in Figure 7. Although some structure is apparent at the base of the light curve, the large central flash predicted by the model is not evidenced. A thermal gradient and/or extinction in the lower atmosphere could cause this feature to be suppressed.
MORIS was internally triggered to take 2 s exposures. The camera settings were full frame, 1 MHz conventional mode, with 2.4× preamplifier gain. Throughout the observations, the air mass ranged from 2.2 to 1.2 and the seeing was approximately 1″. The best light curve, shown in Figure 8, was produced with a 30 pixel radius aperture around the star, with the sky background estimated from an annulus with inner radius of 60 pixels and a width of 10 pixels. A slight mismatch in the level of baseline before and after transit was removed with a trend against time. The instrument was refocused twice when the seeing began to worsen, and there are two features just before ingress and near the midtime associated with those refocusing events.

The transit light curve was fit using the Mandel & Agol (2002) algorithm as implemented by the white-noise model described in Carter & Winn (2009). We assumed that XO-2b has zero obliquity, oblateness, and orbital eccentricity, and we employed a quadratic limb-darkening law assuming $T = 5340$ K, $\log g = 4.48$, $[M/H] = 0.5$, and $V_{\text{micro}} = 2$ km/s. Since the transit was observed with a long-pass filter (effective wavelength 700–900 nm), we used the initial values of $u_1 = 0.3670$ and $u_2 = 0.2850$ for the Sloan $i'$ filter from Claret (2004) and fit for the linear term, $u_1$, while leaving $u_2$ fixed. The best model parameters were found using a Monte Carlo Markov chains method, with the best least-squares-fit values used as initial parameters. Three independent chains of $10^6$ links (minus the first 50,000 points in each) were combined to derive the final parameters, which are the median and 68.3% credible interval values (equivalent to the standard deviation if the distribution is Gaussian). For more details on the modeling, see Adams (2010). Following Fernandez et al. (2009), the orbital period was fixed to $P = 2.615864$ days, and we assumed that $M_\star = 0.971 \pm 0.034 M_\odot$, $R_\star = 0.976 \pm 0.024 R_\odot$, and $M_{\text{planet}} = 0.565 \pm 0.054 M_{\text{Jup}}$.

By fitting the transit on 2008 December 6 jointly with another half-transit observed from MORIS on 2008 December 19,
we derived a planetary radius of $R_{\text{planet}} = 0.955 - 0.024 R_{\text{Jup}}$. This result is slightly smaller than, but consistent with, the value of $R_{\text{planet}} = 0.996^{0.031}_{-0.018} R_{\text{Jup}}$ reported by Fernandez et al. (2009). Additional fit parameters are described in Adams (2010). Correlated noise is present in the light curve, most notably as a sharp increase just after midtransit that was associated with a refocusing event and also coincided with a slight positional change. Consequently, the formal fit errors were inflated by a factor of 3.1 based on an examination using the time-averaged residual method (Pont et al. 2006; Adams et al. 2010). The measured midtime, $2.454, 806.94750 \pm 0.00027 \text{BJD}_{\text{TDB}}$, agrees with the predicted midtime of Fernandez et al. (2009) and no signs of transit timing variation are seen in this light curve. We reached a photometric precision of 0.5 mmag in 2 minutes and a midtime timing precision of 23 s.

4. SUMMARY AND FUTURE WORK

This article introduces a new, high-speed, accurately timed, optical imaging camera system on NASA's 3 m IRTF. The IRTF’s remote observing capabilities make this instrument particularly ideal for targeted, time-sensitive observations, two examples of which are presented here. The observations of a stellar occultation by Pluto and an exoplanet transit by XO-2b demonstrate that the system is capable of taking well-timed, high-quality photometric data. First, an occultation light curve of decent S/N (35 per scale height) was obtained on a fairly faint star (15.8 $R$ magnitude), and the midtime has an accuracy of 0.32 s. The results indicate that the light curve may contain a repressed central flash and that the prediction was extremely accurate. If chords from other stations would have been obtained, these data would be of sufficient quality to characterize Pluto’s atmosphere. Given Hawaii’s unique geographical location, we anticipate that MORIS will play a key role in future occultation observations by Pluto and other large Kuiper Belt objects (e.g., Elliot et al. 2010). Second, the transit data reach the millimagnitude photometric accuracy required for detection and have a timing precision of tens of seconds. Thus, MORIS observations can achieve the level of accuracy needed to reduce the ambiguity between correlated parameters such as orbital inclination, radius ratio, and stellar limb darkening and can possibly reveal variations caused by additional bodies in an extrasolar planetary system.

A key strength of MORIS is the ability to take simultaneous NIR observations with SpeX. Although the results presented here did not make use of that feature, we will explore it in future work. Such multiwavelength observations will be important to occultations because they allow distinction between atmospheric extinction and differential refraction (Elliot et al. 2003). For transit observations, simultaneous multiwavelength observations can help constrain modeling parameter space, provide independent confirmation of light curve timing, and potentially reveal wavelength-dependent features (e.g., Colon et al. 2010). Similarly, the electron-multiplying capability of the system could provide enhanced results and will be studied in future work.

In the presented results, we do not address flat-field calibrations. MORIS exhibited a significant (factor of 2) radial variation in brightness, the exact structure of which varied as a function of pointing and ambient illumination. The IRTF is optimized for infrared observations rather than visible, and we have confirmed that the background brightness effect was the result of scattered light. We designed a new optical path and fore optics box, which include a stop and multiple baffles that effectively eliminate all light that is not from the secondary mirror. We will present details of the modified instrument in a subsequent article.

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REFERENCES

Elliot, J. L. 1979, ARA&A, 17, 445
———, 2007, AJ, 134, 1
———, 2010, Nature, 465, 897
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, P. D. 1996, AJ, 111, 1748


McDonald, S. W., & Elliot, J. L. 2000, AJ, 120, 1599


Young, L., Buie, M., French, R., Olkin, C., Regester, J., Ruhland, C., & Young, E. 2006, BAAS, 38, 542

Phelan, D., Ryan, O., & Shearer, A., eds. 2008, High Time Resolution Astrophysics, (Dordrecht: Springer), 351