Observations of Transiting Exoplanets with Differential Photometry

Brett Morris

University of Maryland

bmorris3@astro.umd.edu

ABSTRACT

Preliminary observations and computational methods for analysis are presented for observing celestial objects with time-varying intensity, in particular transiting exoplanets. Transits occur when a planet orbiting a star other than the sun (an exoplanet) passes between the Earth and the host star, slightly dimming the apparent intensity of the star. CCD images of the host star of one such exoplanet, HD 189733b, are recorded during predicted transits at the University of Maryland Observatory (UMO) on a small (152 mm) refracting telescope. Differential photometry algorithms compare the relative brightness of the host star to other nearby, non-variable stars in the field and detect the small change in brightness associated with a planetary transit, on the order of tens of millimagnitudes. The first successful exoplanet observations at UMO are presented and discussed, as well as possible implications for exoplanetary studies conducted by amateur and small observatories.

1. Introduction

Exoplanets are being discovered by the hundreds today. The two principal methods of exoplanet detection involve: (a) measuring the radial velocity of a star for perturbations caused by a planet, or (b) measuring the change in intensity of a host star as a planet passes between the star and Earth, known as a transit.

HD 189733b has been a favorable exoplanet for transit observations since its discovery by Bouchy et. al in 2005 (Bouchy et al.). It orbits a nearby visual magnitude $V = 7.67$, K dwarf star with a period of 2.2 days at a distance of 19.2 pc in the constellation Vulpecula (Bouchy et al.; Sing et al.). The brightness of the host star and its location – passing through high altitudes in the summer sky for observers in the northern hemisphere – make it an attractive target for small college observatories and serious amateurs.

Differential photometry is an observing technique used to compare the relative changes in brightness between one star and others nearby in the sky. An average is taken over the instrumental intensity of a set of a few to many stars, called control stars, in CCD images over a period of time to account for changing atmospheric conditions. The intensity measurements of the star being analyzed for variation, called the target star, are then corrected for the atmospheric effects measured in the control stars, revealing its intrinsic variations.

Observations of transiting exoplanets are being collaboratively compiled and compared by small college observatories and skilled amateurs around the world (Poddany, Brat, and Pejcha). Seagroves et al. argue that this class of observers have distinct advantages to offer for monitoring transiting exoplanets. These advantages include diverse longitudinal locations, strength in numbers for multiple simultaneous follow ups and low-cost observations (Seagroves et al.). Observatories in locations with bright light pollution and low elevation can still prove useful in bright transiting exoplanet observations.

Here I present the first observations of an exoplanet at the University of Maryland Observatory, as well as an original differential photometry algorithm for accessible transiting exoplanet detection for college observatories and serious amateurs. The observing techniques and apparatus are detailed in the Observational Methods section, the differential photometry algorithm is introduced in Analysis, some observations are shown in Results and discussed in the Discussion section.

2. Observational Methods

2.1. Apparatus

All observations discussed here were taken with a 152mm Astro–Physics f/9 refracting telescope on an AP900 equatorial mount temporarily installed at the University of Maryland Observatory (UMO) in College Park, MD, US, located $<$6 km from the District of Columbia at an elevation of $\sim$100 m above sea level. Images were recorded on an SBIG ST-10 CCD camera with 6.8 square micron pixels in an array of dimensions 2184×1472. The field of view was approximately $0.5^\circ \times 0.75^\circ$ with a focal reducer in place. The CCD was cooled to -5 °C, controlled by MaxIm DL (Version 5.12). The Baader R-CCD red filter was used exclusively in the presented observations.

2.2. Observing Techniques

Dark frames are collected by exposing the CCD without sky illumination and recording the background noise, hot pixels and thermal noise, which is then subtracted from each image of the sky. Flat fielding is performed by exposing the CCD to light projected evenly on a screen in the observatory. The isotropic light field becomes attenuated by dust and other imperfections in the optical path of the telescope resulting in systematic variations in the flat field exposures. Several of these exposures are averaged and the resulting image is normalized by the mean pixel intensity. All sky exposures are divided by this "master flat."

A red filter was used for all photometric observations. A typical photometric event such as an exoplanet transit or a short period pulsating variable star peak event happens over the course of several hours. The altitude of the object of interest can change greatly in that time leading to changing atmospheric extinction throughout the night. This extinction also varies with wavelength, affecting the longer wavelengths less than shorter ones. Thus, the red filter was used to select the light from any color star that is least affected by atmospheric extinction.

Defocusing the telescope is commonly used in differential photometry to spread the light of a bright star over many pixels. The greater imaging area covered by the star reduces some systematic errors unaccounted for by the dark frames and flat fields associated with focusing large amounts of the light on individual pixels. The decreased intensity of the light on each individual pixel also allows for longer exposures without risk of saturation, which can in effect smooth out some atmospheric noise that happens on short time scales. Transit observations are presented here with and without defocusing.

After the CCD is cooled and dark frames are exposed, the star of interest is found and centered in the field of view. The target star is centered to keep it in the frame despite the imperfect tracking of the telescope. The particular telescope used here, like many others, is in slightly off–polar alignment, causing stars to drift in the field of view throughout the course of a night. A favorable alignment keeps the target star in the frame for as long as possible while also orienting itself to maximize the number of control stars in the frame for comparison. Exposure lengths are adjusted so that the brightest control stars are recording maximum pixel intensities significantly below saturation.

3. Analysis

A suite of differential photometry software named "`oscaar`" (for Open Source differential photometry Code for Amateur Astronomical Research) was developed in Python to generate light curves from the series of images recorded by the CCD. The code has several key phases of analysis which will be discussed here in some detail, namely star tracking, aperture photometry, and differential comparison. This section will discuss analysis of "stars" or "objects" in general. These methods can be used to observe exoplanet transits, variable stars and rotating asteroids among others.

The drift of the stars due to imperfect telescope tracking is a ubiquitous obstacle to iterative measurement of star magnitude in low–power observatories. The problem of tracking object positions becomes unavoidable for observations of asteroids, for example, which can move significantly with respect to the sky in a few hours. `oscaar` takes user input from SAOImage DS9 to record approximate centroid positions and radii of target and control stars chosen by the user in the first image in a photometry set. The explicit choice of objects by the user provides a check against unfavorable objects for photometry. Gaussian functions are fit to the intensities in the regions immediately around the object centroids using χ^2 minimization. The coordinates of the object centroids and the σ parameter corresponding to the radial spread of the object are recorded and used as initial estimates in the fit for the next frame. This method of tracking is not affected by the independent motion of one or more of the tracked objects.

The object centroids and radii provide the basis for the aperture photometry measurements. The source aperture is centered on the fit centroid with radius 5.5σ where σ is again the Gaussian width parameter from the fitting process. This large factor of σ was chosen to loosely enclose $> 99\%$ of the source light even in poor Gaussian fits. The sky aperture has concentric radii 5.5σ to 7.5σ. The median of the intensities in the sky aperture is interpreted as a measurement of the background intensity of the sky. This background value is subtracted from each pixel intensity in the source aperture and the resulting array is summed to derive the instrumental intensity of the object. The instrumental magnitude is converted to an astronomical magnitude. These calculations are summarized symbolically for clarity in the Appendix.

The magnitude of the control stars at each time is averaged into one aggregate control intensity measurement of the variations of the stars throughout the period of observation. The differential photometric measurement of the variation in the target star is simply the magnitude of the target star subtracted from this aggregate control intensity. A star with no variability relative to the control stars is represented by a function of constant magnitude throughout time; objects with variability show non–zero and time–varying slopes.

`oscaar` is intended for small observatories and serious amateurs. It is commanded by a user edited plain text parameter file that controls the running parameters of the algorithms and indicates the input files. Users need not interact with the underlying Python code to generate light curves from raw CCD images, and a graphical user interface is provided to display the control and target star differential magnitude light curves. A free open source distribution of `oscaar` is available online[1].

4. Results

The first successful observation of an exoplanet at UMO was produced in collaboration with UM undergraduate Harley Katz. A time series of images of HD 189733b and the surrounding star field was collected during a predicted transit (Poddany, Brat, and Pejcha). Light curves demonstrating the diminished intensity of the star during the transit were generated by `oscaar` using 25 bright comparison stars ranging in magnitude from about 8–12 magnitude. This magnitude range is constrained by low signal from stars dimmer than 12 mag and lack of stars above 8 mag. The telescope was well–focused, necessitating short (7 s) exposures. Over 190 minutes, 607 images were collected. The resulting light curve in Figure 1 shows a 28.3 $\pm$ 0.5 mmag attenuation of the star light at the predicted time of transit. The expected depth is 28.2 mmag (Bouchy et al.).

A second set of observations were collected using the defocusing method. The light was effectively defocused by the extremely humid atmosphere in College Park, which approached 94% humidity toward the end of the transit. The centroid fitting routine produced a mean sigma fit parameter — corresponding to the radial spread of each star — 30.5% larger in the naturally defocused run than in the well–focused data set. The widely distributed light decreased the peak intensity at stellar centroids and enabled exposures to be increased to 20 s. 37 control stars were chosen for differential photometry, producing the light curve in Figure 2.

The observations were repeated on a night with 60% humidity (less optically significant) and intentional defocusing of the telescope components. The telescope was focused on globular cluster M13 and defocused such that the intensity of a typical star centroid decreased by a factor of 2.5 in the same exposure time. 28 control stars were tracked in 337 frames with 12 s exposures. The results shown in Figure 3 confirm the benefits of defocusing.

[1] `http://oscaar.googlepages.com/`

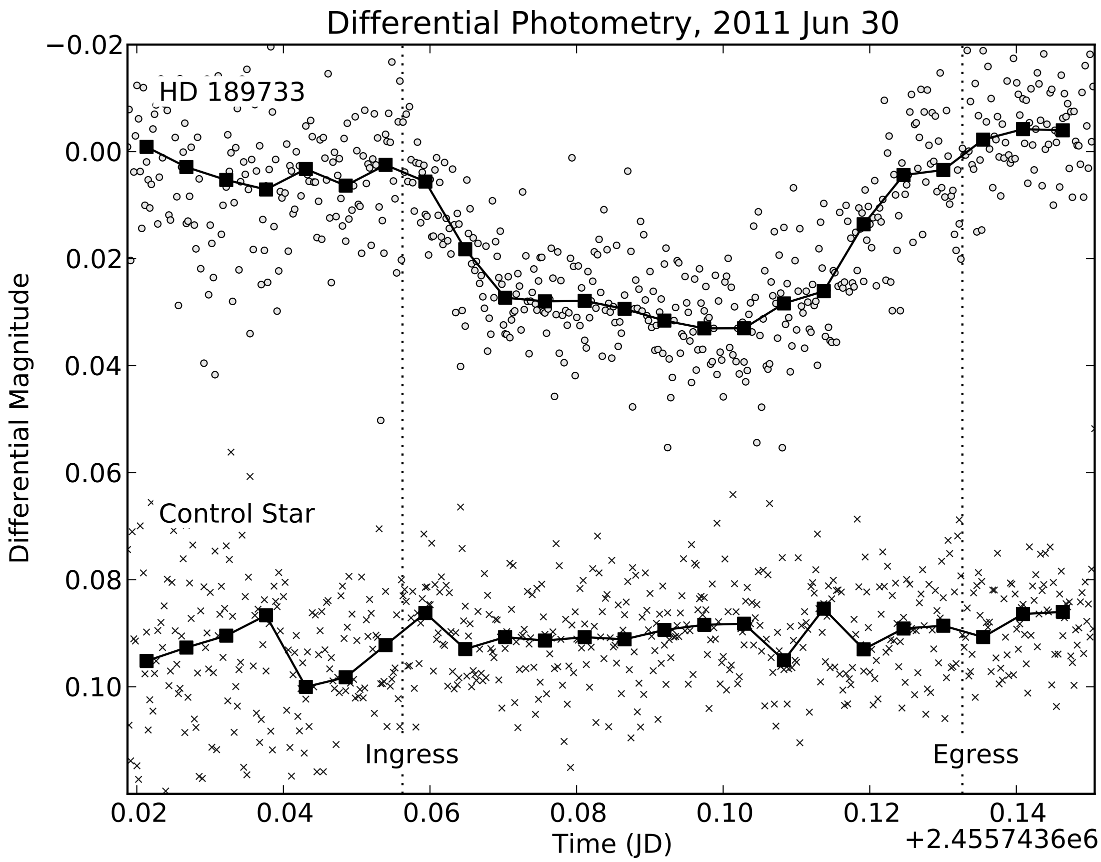

Fig. 1.— The first successful exoplanet transit light curve from UMO. The set of circles represent the magnitude of host star HD 189733. The set of xs represent the magnitude of a non-variable control star, HIP 98523. The connected dark squares represent 25 point median binning. The control data is given a vertical displacement for clarity.

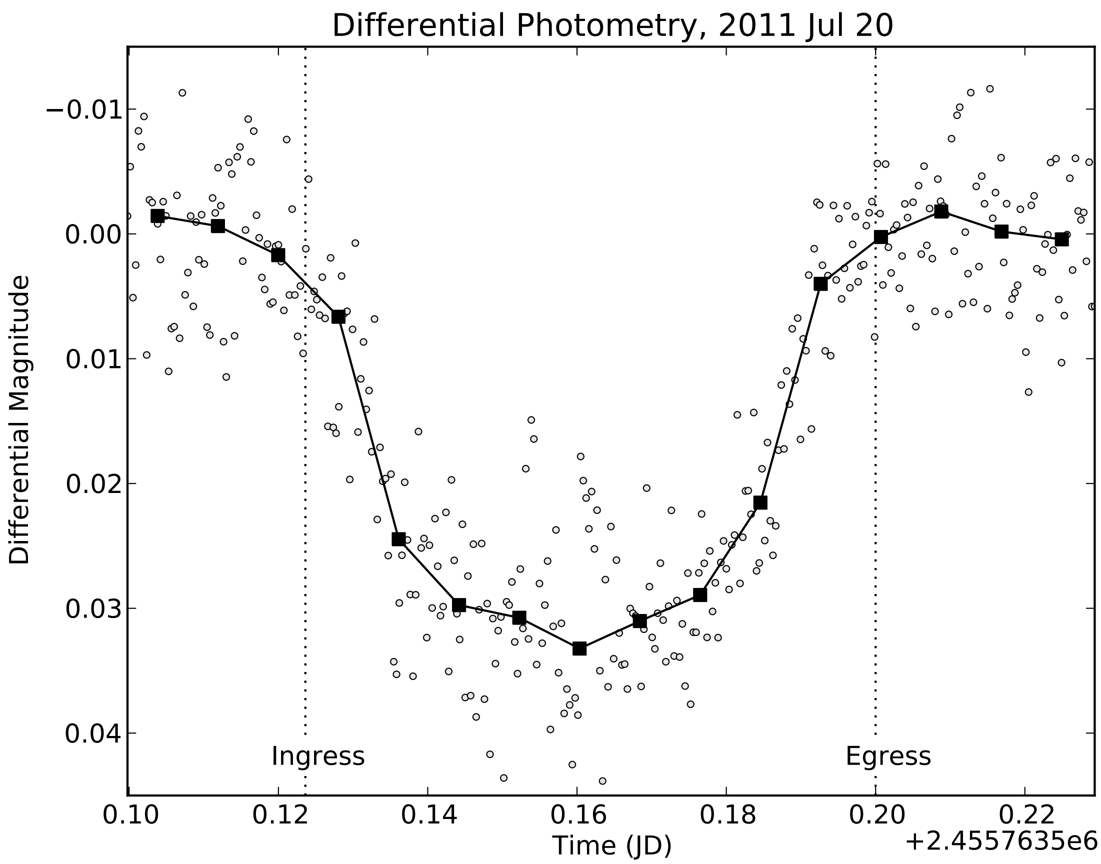

Fig. 2.— Second photometric observation of HD 189733b, with natural defocusing (humidity and haze). The connected dark squares represent 22 point median binning.

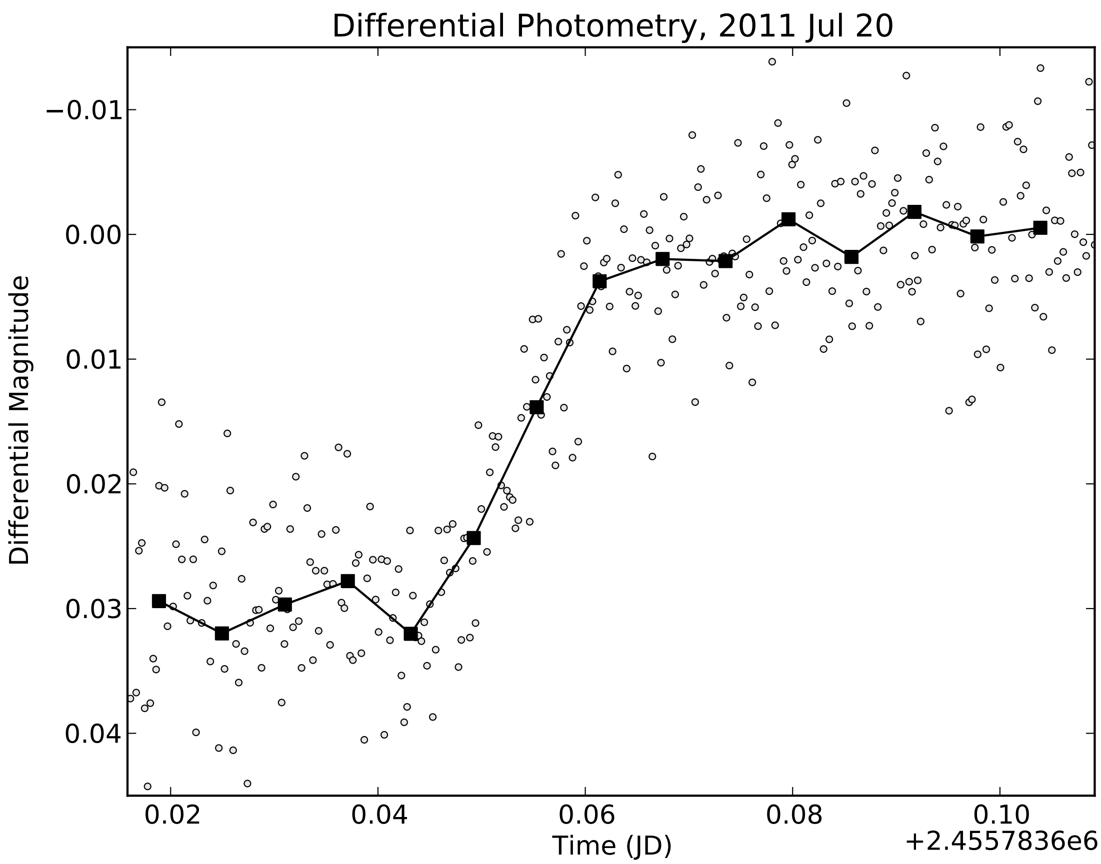

Fig. 3.— Third photometric observation of HD 189733b, with intentional defocusing. The observed depth is 29.0 ± 0.4 mmag. The connected dark squares represent 25 point median binning. The transit observation is incomplete due to poor weather at ingress.

5. Discussion

The results confirm that exoplanet transit light curves can be collected by small observatories in non–ideal locations. UMO is well within the Washington, DC light pollution "bubble," which is considered a Bortle–scale 9 or 10 site (Cinzano, Falchi, and Elvidge). College Park is heavily populated, $\sim$100 m above sea level and typically very humid. As discussed in the Results section, a verified method for defocusing can be to view the star on nights of high humidity (see Figure 2), which successfully reduces noise in the light curve. In the case of bright transiting exoplanet detection, atmospheric conditions that can otherwise be crippling to astronomical research can benefit transit observations.

Light pollution at UMO significantly increases the background sky intensity, effectively making the signal–to–noise ratio poorer for dim stars. The number of control stars available in a given field is therefore reduced due to the location of UMO. There are still many viable control stars in star fields as dense as the region surrounding HD 189733. The number of stars does not significantly change the light curve in a differential photometric observation of $>$20 stars. This suggests that more sparse star fields will still produce quality light curves of bright transiting exoplanets at small observatories.

The success of the defocusing technique can be attributed to several factors. The increased exposure length compensates for the decreased intensity of the brightest pixels in each frame. The longer exposure length may be integrating over a time cycle longer than the atmospheric fluctuations that are a source of noise in the shorter exposures. Defocusing also provides a natural form of dithering. The star light is spread out over more pixels, lessening the significance of pixel–to–pixel variations that may have eluded correction in the dark frame and flat field processing. The imperfect polar alignment of the telescope may be a source of uncorrected systematic error. The target star drifted $\sim$275 pixels in the 2011 Jun 30 observation, which significantly spreads the observation over many pixels. The flat fielding normalization and dark frame subtraction are assumed to remove any systematic effects along the length of the detector and some corrected images were visually inspected to ensure the calibration process successfully removed obvious systematic effects.

It has now been shown that small college observatories like UMO can produce quality light curves of transiting exoplanets. It should be noted that these observations were recorded using standard college observatory apparatus, and can likely be repeated in other small observatories. The quality of these observations is likely to increase as the observing techniques are refined and preliminary observations of dimmer transiting exoplanets suggest that stars dimmer than HD 189733 by several magnitudes can be observed at UMO. Online transit predictions by services like those of Poddany et al. provide up–to–date ephemerides on observable transiting exoplanets. These accurate predictions minimize observing time for follow-up observations by allowing observers to plan observing sessions to the minute. Poddany et al. also provide a streamlined, centralized system for updating these ephemerides with new user collected data. The author plans to monitor candidate transiting exoplanets for follow–up observations to constrain ephemerides, and to contribute to these databases with the results that are collected.

6. Conclusions

Small observatories such as the University of Maryland Observatory are capable of recording light curves of bright transiting exoplanets such as HD 189733b with common apparatus. Rather simple differential photometry algorithms can define transits of reasonable quality with ∼20 control stars.

7. Appendix

Presented here for clarity is a mathematical summary of the flat field normalization and dark frame subtraction process applied to each aperture photometry source.

Given

$\{s_i\}$ is the set of intensities of the source pixels
$\{\sigma_i\}$ is the set of intensities of the sky (background) pixels
$\{d_i\}$ is the set of intensities of the dark frame
$\{f_i\}$ is a set of intensities of the flat field (of which there are several),

the set of the intensities of the normalized average of the flat fields $\{F_i\}$ is given by

$$\{F_i\} = \frac{\overline{\{f_i\}}}{\mathrm{median}(\overline{\{f_i\}})} \tag{1}$$

The instrumental magnitude I of the star is then

$$I = \sum_{all\ s} \left\{ \frac{s_i - \mathrm{median}\{\sigma_i\} - d_i}{\{F_i\}} \right\} \tag{2}$$

and the differential astronomical magnitude is given by

$$m = 2.5 * \log_{10} I \tag{3}$$

The author would like to thank Elizabeth Warner (UMCP), the Observatory Coordinator, for providing access to the facilities at the University of Maryland Observatory and training with the telescope. Some of the observatory setup procedures were completed with assistance from fellow undergraduate Harley Katz (UMCP) on several occasions. This project was inspired by a conversation with Dr. David Charbonneau (Harvard) and is being continued with Dr. Drake Deming (UMCP).

Bibliography

Bouchy, F., S. Udry, Mayor M, C. Moutou, F. Pont, N. Iribarne, R. DeSilva, S. Ilovaiski, D. Queloz, N. C. Santos, D. Segransan, and S. Zucker. "ELODIE Metallicity-biased Search for Transiting Hot Jupiters: A Very Hot Jupiter Transiting the Bright K Star HD 189733." *Astronomy and Astrophysics* 444.1 (2005): L15-19. Print.

Cinzano, P., F. Falchi, and C. D. Elvidge. "The First World Atlas of the Artificial Night Sky Brightness." *Monthly Notices of the Royal Astronomical Society* 328.3 (2001): 689-707. Print.

Poddany, Stanislav, Lubos Brat, and Ondrej Pejcha. "Exoplanet Transit Database. Reduction and Processing of the Photometric Data of Exoplanet Transits." *New Astronomy* 15.3 (2010): 297-301. Print.

Seagroves, Scott, Justin Harker, Gregory Laughlin, Justin Lacy, and Tim Castellano. "Detection of Intermediate-Period Transiting Planets with a Network of Small Telescopes: Transitsearch.org." *The Publications of the Astronomical Society of the Pacific* 115.814 (2003): 1355-362. Print.

Sing, D. K., F. Pont, S. Aigrain, D. Charbonneau, J. M. Desert, N. Gibson, R. Gilliland, W. Hayek, G. Henry, H. Knutson, A. Lecavelier Des Etangs, T. Mazeh, and A. Shporer. "Hubble Space Telescope Transmission Spectroscopy of the Exoplanet HD 189733b: High-altitude Atmospheric Haze in the Optical and Near-ultraviolet with STIS." *Monthly Notices of the Royal Astronomical Society* 416.2 (2011): 1443-455. Print.