# Externally Dispersed Interferometry for Precision Radial Velocimetry

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## ABSTRACT

Externally Dispersed Interferometry (EDI) is the series combination of a fixed-delay field-widened Michelson interferometer with a dispersive spectrograph. This combination boosts the spectrograph performance for both Doppler velocimetry and high resolution spectroscopy. The interferometer creates a periodic spectral comb that multiplies against the input spectrum to create moiré fringes, which are recorded in combination with the regular spectrum. The moiré pattern shifts in phase in response to a Doppler shift. Moiré patterns are broader than the underlying spectral features and more easily survive spectrograph blurring and common distortions. Thus, the EDI technique allows lower resolution spectrographs having relaxed optical tolerances (and therefore higher throughput) to return high precision velocity measurements, which otherwise would be imprecise for the spectrograph alone.

## 1. INTRODUCTION

Externally Dispersed Interferometry (EDI) is a new technology for precision Doppler velocimetry that is both more efficient and less expensive than traditional high resolution spectrographs.[1–17] This technique increases the responsivity of a low-dispersion spectrograph to sharp spectral features which would normally be unresolved. The first exoplanet results are arriving from these instruments as they are starting to come online. An EDI recently discovered a new exoplanet around the star HD 102195 in Virgo.[13] A multi-object EDI is being tested at the 2.5 m Sloan telescope.[17] An NSF funded project is underway to field an EDI at the cassegrain output of the Mt. Palomar Observatory 200 inch telescope in series with the TripleSpec near infrared (0.8–2.4 $\mu m$) spectrograph being built by Cornell University.[18] This will find low mass exoplanets around low mass stars.[7,9,10]

An EDI is the series combination of a fixed-delay interferometer with a dispersive spectrograph (Fig. 1). The interferometer generates fringes which shift in phase in response to a Doppler velocity, and the disperser separates the fringes of different wavelengths on the detector array so that they can be detected at high visibility. The advantages of an EDI over high-resolution spectroscopic velocimetry are three-fold:

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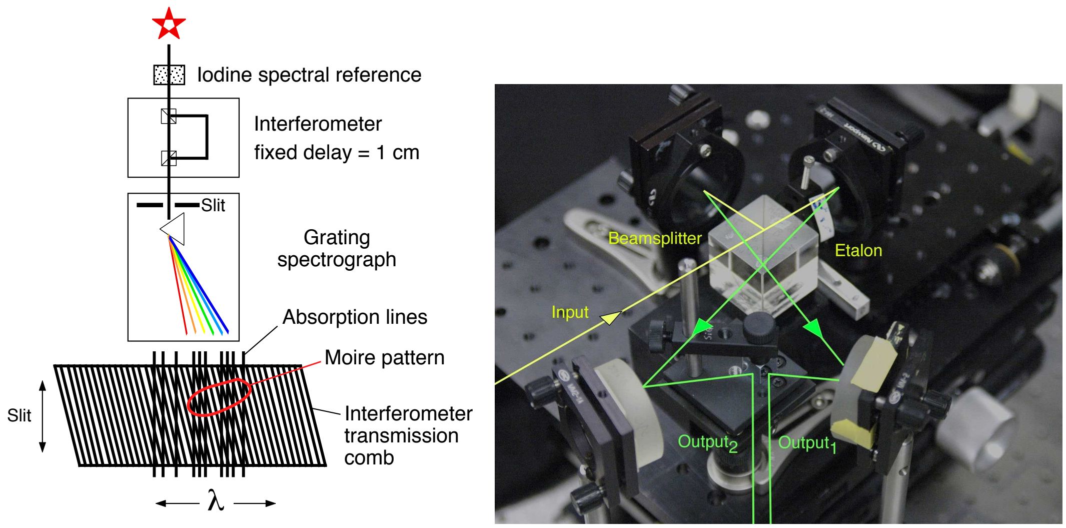


**Figure 1.** [Left] EDI concept. A sinusoidal transmission comb created by the interferometer is multiplied against the stellar spectrum, adding moiré fringes to the ordinary spectrum. The moiré and ordinary components are separated during analysis. The moiré fringes change phase in proportion to the star's Doppler velocity. [Right] Example EDI apparatus, having dual outputs for high efficiency.

1. **The cost, weight, and size of the spectrograph and detector are greatly reduced.** Much lower resolution spectrographs can be used to return precision Doppler velocities. For example, the EDI used to detect the planet around HD 102195 had a resolution[13] of only $\lambda/\Delta\lambda = 5000$.

2. **The throughput and sensitivity of an EDI is increased.** Lower resolution spectrographs usually have better throughput; the EDI preserves this property. For example, the Exoplanet Tracker on the 2.1 meter Kitt Peak telescope can perform precision radial velocity (RV) measurements on sources as faint as 10th magnitude (15 minutes to achieve 8 m/s for V=8, Ref. 19); this compares favorably to HIRES on the 10 meter Keck telescopes! Wider bandwidths can be used using the interferometer signal as a wavelength fiducial linking spectral features across the band. The increased number of spectral lines covered improves RV precision and sensitivity. Smaller telescopes can be used for a given target brightness, which often have more time available for higher cadence observations. Alternatively, more targets are accessible to large telescopes, possibly including the faint stars targeted for deep transit searches, including the Kepler field.

3. **The EDI measurement is more robust to systematic and instrumental effects.** The stepping manner of measuring moiré pattern phases eliminates fixed pattern errors such as those due to detector or optics blemishes by acting as a built-in flatfielding—they are not synchronous with the stepping. Common spectrograph irregularities, such as drifts in the focal spot position and diameter on the detecting array, do not strongly affect the EDI observable of fringe phase. This is due to the differential nature of a moiré pattern in comparing the stellar and interferometer sinusoidal combs. The interferometer comb can be thought of as a set of fiducials coupled to the science signal

and follow it through the instrument. Distortions affecting the science signal are also applied to the interferometer comb. We have estimated that the EDI is 1000 to 10,000 times more robust to translation of the focal spot, and 10 to 100 times more robust to change in focal spot diameter.

## 2. INSTRUMENT METHOD

The transmission spectrum of an interferometer of delay $\tau$ is sinusoidal versus wavenumber ($\nu = 1/\lambda$). Passing starlight through an interferometer multiplies the periodic sinusoidal interferometer comb by the stellar spectrum. Heterodyning between similar spacing of features (along the dispersion axis) in the stellar spectrum and the sinusoidal comb creates beating between frequencies. These "Moiré patterns" are broader and more easily survive the blurring of a spectrograph than the original narrow features.

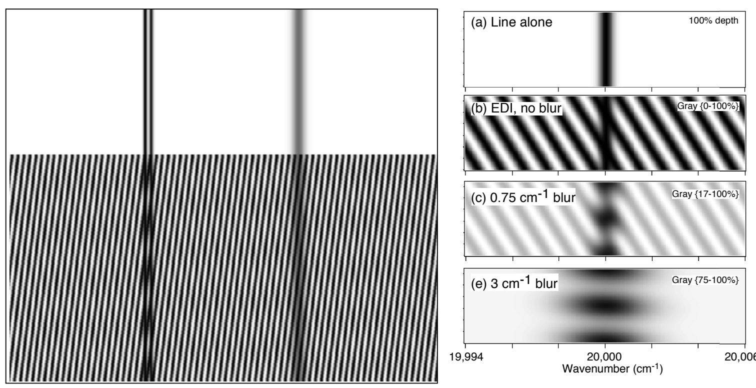


**Figure 2.** (Left) The moiré fringes created by overlaying a sinusoidal transmission on an input spectrum distinguishes a doublet from a singlet, satisfying the classical definition of a resolution increase. (Right) Moiré fringes persist under spectrograph blurring.

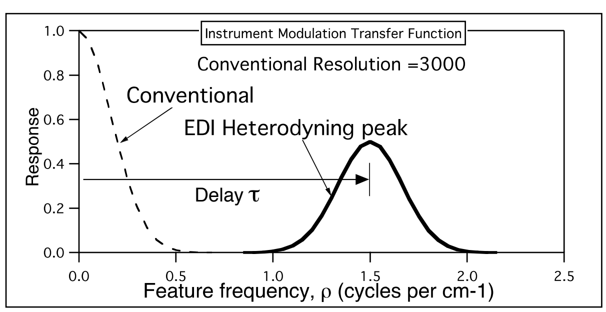


**Figure 3.** The EDI sensitivity has a peak centered at high spatial frequencies chosen by the interferometer delay $\tau$. This can be placed where more Doppler information content exists in the stellar spectrum, which is often at high spatial frequencies beyond the sensitivity peak of the spectrograph alone (dashed curve).

A Doppler velocity change in the stellar spectrum produces a phase change in the moiré phase. However, a slight drift in the interferometer delay, such as due to thermal changes, also will cause a phase shift. The solution is to simultaneously record a calibrant spectrum (such as iodine vapor, for visible light) along with the stellar spectrum. The Doppler shift is the difference between the stellar and calibrant moiré phases.

## 3. DOPPLER QUALITY FACTOR

The radial velocity measurement noise is a function of the characteristic spectral derivative and the number of photons recorded. The photon limited velocity noise ($\delta V$) in a radial velocity measurement is given by[20]

$$\delta V = \frac{c}{Q}\frac{1}{\sqrt{N}} \tag{1}$$

where $N$ is the total number of detected photons summed over the bandwidth in question. The $Q$ is a dimensionless normalized RMS average of the spectrum's derivative. Therefore, Q is high and the noise is low when the spectral lines are numerous and narrow. The Doppler velocity signal to noise ratio is proportional to $Q$. Reference 10 shows how to calculate Q for a stellar spectrum of a cool star (Fig. 4). For calculating $\delta V$ when $Q(\nu)$ or the intensity $dN/d\nu$ varies with $\nu$, one integrates $Q^2(\nu)dN/d\nu$ over the bandwidth in question, takes the square root, and substitutes that value for $Q\sqrt{N}$ in Eq. 1.

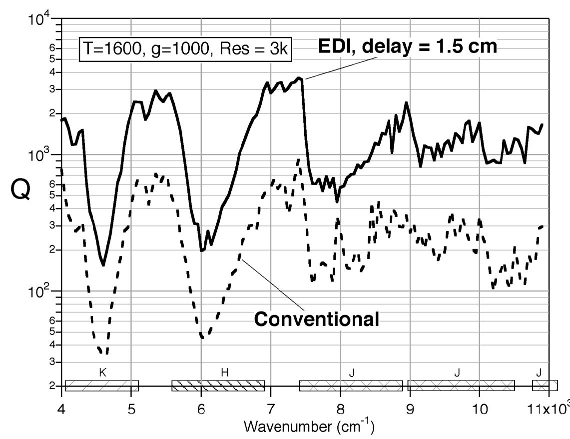


**Figure 4.** A spectrum's Doppler quality ($Q$) versus wavenumber ($\nu$), calculated for a stellar model having temperature T=1600, gravity g=1000, and no rotational blurring. Shown are conventional $Q$ and EDI $Q$ for native spectrograph resolution Res=3k and interferometer delay of 1.5 cm.

## 4. COMPARISON TO OTHER METHODS

The EDI is distinguished from *internally* dispersed interferometers such as the Spatial Heterodyning Spectrometer[21] by having the dispersive element *outside* the interferometer cavity rather than inside, so that ray angles inside the interferometer, which affects fringe phase, are the same for all wavelengths. This allows the simultaneous bandpass for the EDI to be essentially unlimited, (whereas for the SHS it is very limited).

In EDI Both complementary interferometer outputs can be directed to the spectrograph (Fig. 1 right), so for ideal optics every photon that enters the interferometer passes to the spectrograph and contributes to a Doppler velocity signal.

In conventional Doppler radial velocimetry, a dispersive spectrograph is used having a minimum resolving power of about 50,000. Resolutions less than this are insufficient to prevent neighboring spectral features from blending together, reducing the slope on the edge of each line. (A large slope is needed to produce a detectable intensity change for a given Doppler wavelength change.) Unfortunately, spectrographs having this minimal resolution are very large and expensive for large telescopes, because spectrograph size scales with resolution, bandwidth and telescope diameter, and spectrograph cost and weight scale nonlinearly with spectrograph size.

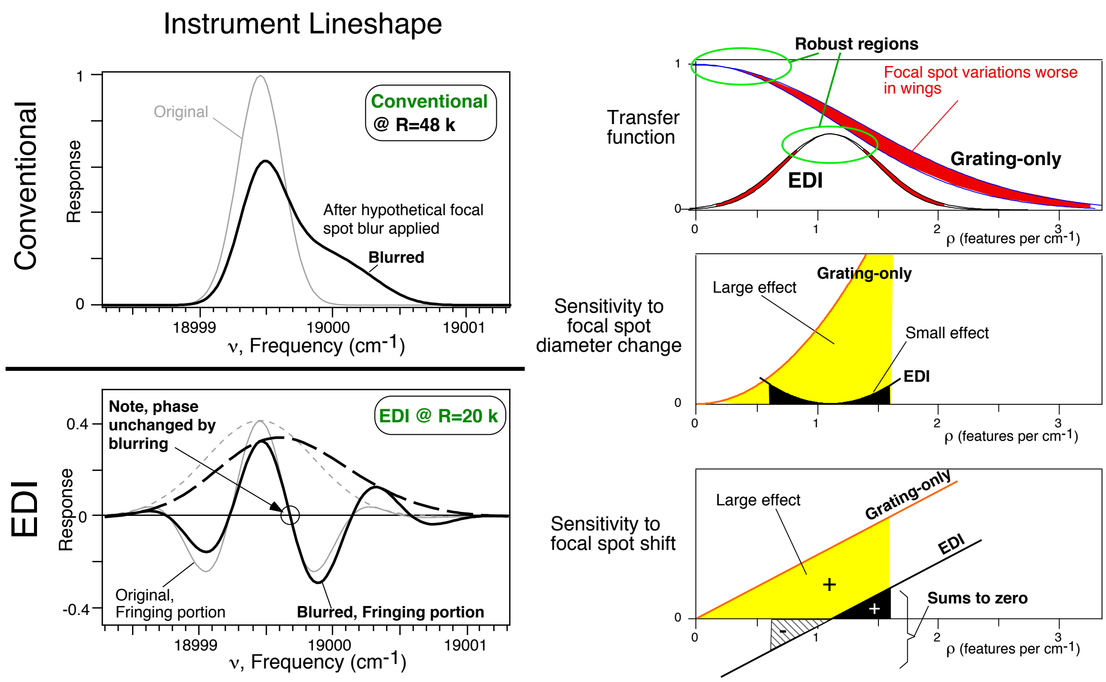


**Figure 5.** (Left) Numerical simulation of the effect of spectrograph instrument line shape distortion (black vs gray) on conventional (top) and EDI data (bottom). Note that the fringe phase zero crossing (circle) is unchanged. (Right) Robustness of EDI instrument line shape to focal spot motion and diameter change.

## 5. INFRARED RV AND T-EDI

RV Doppler measurements[22] have proved to be the most successful way of finding extrasolar planets to date. It appears this method may fall short of actually finding Earthlike planets in the habitable zones of Sunlike stars, because the 0.1 $\mathrm{m\,s^{-1}}$ velocity amplitude induced on the star around the system's barycenter is smaller than pulsations of the stars themselves.

RV searches targeting lower mass stars present an opportunity to overcome this limitation because two factors increase the velocity signatures of habitable exoplanets; see Figure 6. First, the star's reflex motion velocity is inversely proportional to the star's mass; this presents one factor of 10 improvement. Second, low-mass stars have lower surface temperatures than the Sun, and their habitable zones are correspondingly closer. RV amplitude is inversely proportional to the square root of the star-planet separation; this adds another factor of $\sim 3$ improvement.

Finding planets around low mass, cool stars is also of interest for direct imaging studies because the contrast requirements are lowered. This can ease design requirements by a factor of $\sim 1000$.

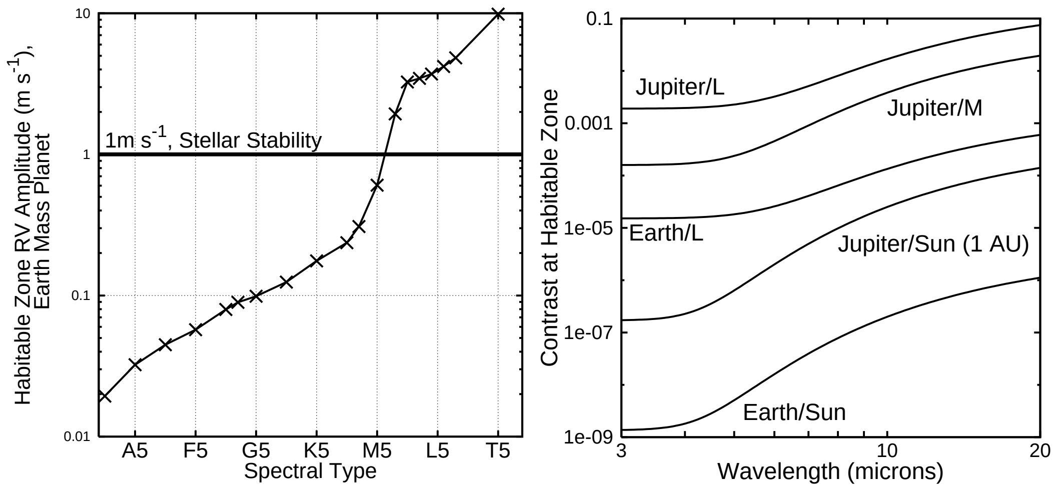


**Figure 6.** (Left) The radial velocity signature of an earth-mass planet in the habitable zone as a function of stellar spectral type. The RV technique can detect Earthlike planets around stars later than $\sim$ M5; the RV signature for earlier spectral types is often smaller than the RV stability of the star's atmosphere. (Right) The star-planet contrast for planets in the habitable zones of a variety of dwarf star types, as a function of observing wavelength. Blackbody spectra are assumed for both star and planet, where the planet also reflects starlight. Not shown are spectral features in certain windows which might decrease the contrast.

Low mass stars are intrinsically faint and most of their light is found at near infrared wavelengths. No current system is capable of observing these stars with RV precisions better than $\sim$ 100 $\mathrm{m\,s^{-1}}$; a few early M dwarfs are accessible to Iodine-cell high resolution RV, but these extend only to about M3.

The TripleSpec instrument is a low resolution ($R \sim 2700$), wide bandwidth (simultaneous coverage of $800 - 2400\,\mathrm{nm}$) spectrograph being built for the Palomar 200" telescope by Cornell, for which an EDI unit is being constructed, (hence "T-EDI") . This EDI combination boosts the TripleSpec effective spectral resolution by a factor of $3 - 7\times$, and the associated Doppler velocity precision, while maintaining the high throughput and bandwidth of the low resolution system. The large bandwidth and high throughput of the resulting instrument will allow faint, cold stars to be studied. It will be capable of Doppler velocity measurements with precisions of better than 3 $\mathrm{m\,s^{-1}}$, and for very faint stars (infrared $H \sim 13$ magnitudes) 10 $\mathrm{m\,s^{-1}}$. This will be used to search for Earthlike planets in the habitable zones of low mass stars.

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## REFERENCES

1. D. Erskine, "Single and Double Superimposing Interferometer Systems," *US Patent* **6,115,121**, Issued Sept. 5, 2000.

2. D. Erskine, "Combined Dispersive/Interference Spectroscopy for Producing a Vector Spectrum," *US Patent* **6,351,307**, Issued Feb. 26, 2002.
3. D. Erskine, "An Externally Dispersed Interferometer Prototype for Sensitive Radial Velocimetry: Theory and Demonstration on Sunlight," *PASP* **115**, pp. 255–269, 2003.
4. D. J. Erskine and J. Edelstein, "Interferometric Resolution Boosting for Spectrographs," in *Ground-based Instr. for Astr. Ed. A. Moorwood, I. Masanori.*, *SPIE Proc.* **5492**, pp. 190–199, 2004.
5. D. Erskine and J. Edelstein, "High-res. Broadband Spectral Interferometry," in *Future EUV/UV & Vis. Space Astrophys. Missions and Instr., ed. J. Blades, O. Siegmund*, *SPIE Proc.* **4854**, pp. 158–169, 2003.
6. J. Edelstein and D. Erskine, "High Resolution Absorption Spectroscopy using Externally Dispersed Interferometry," in *UV, X-ray & Gamma Ray Astr. Space Instrm.*, *SPIE Proc.* **5898**, pp. 297–307, 2005.
7. J. Edelstein, D. J. Erskine, J. Lloyd, T. Herter, M. Marckwordt, and M. Feuerstein, "The TEDI instrument for near-IR radial velocity surveys," in *Ground-based and Airborne Instr. for Astr. Ed. I. McLean, & I. Masanori*, *SPIE Proc.* **6269**, 2006.
8. D. Erskine, J. Edelstein, M. Feuerstein, and B. Welsh, "High Resolution Broadband Spectroscopy using an Externally Dispersed Interferometer," *ApJ* **592**, pp. L103–L106, 2003.
9. D. Erskine, J. Edelstein, D. Harbeck, and J. Lloyd, "Externally Dispersed Interferometry for Planetary Studies," in *Techniq. & Instrm. for Detect. Exo-planets*, *SPIE Proc.* **5905**, pp. 249–260, 2005.
10. D. J. Erskine, J. Edelstein, J. Lloyd, and P. Muirhead, "Noise studies of externally dispersed interferometry for Doppler velocimetry," in *Ground-based and Airborne Instrum. for Astron. Ed. I. McLean, I. Masanori.*, *SPIE Proc.* **6269**, 2006.
11. D. Erskine and J. Ge, "Novel Interferometer Spectrometer for Sensitive Stellar Radial Velocimetry," in *Imaging the Universe in Three Dimensions: Astrophys. with Advanced Multi-Wavelength Imaging Devices*, W. van Breugel and J. Bland-Hawthorn, eds., *ASP* **195**, p. 501, 2000.
12. J. Ge, D. Erskine, and M. Rushford, "An Externally Dispersed Interferometer for Sensitive Doppler Extra-solar Planet Searches," *PASP* **114**, pp. 1016–1028, 2002.
13. J. Ge, J. van Eyken, S. Mahadevan, C. DeWitt, S. R. Kane, R. Cohen, A. Vanden Heuvel, S. W. Fleming, P. Guo, G. W. Henry, D. P. Schneider, L. W. Ramsey, R. A. Wittenmyer, M. Endl, W. D. Cochran, E. B. Ford, E. L. Martín, G. Israelian, J. Valenti, and D. Montes, "The First Extrasolar Planet Discovered with a New-Generation High-Throughput Doppler Instrument," *ApJ* **648**, pp. 683–695, 2006.
14. J. Ge, "Fixed Delay Interferometry for Doppler Extrasolar Planet Detection," *ApJ* **571**, pp. L165–168, 2002.
15. J. Ge, "Erratum: Fixed Delay Interferometry for Doppler Extrasolar Planet Detection," *ApJ* **593**, p. L147, 2003.
16. J. C. van Eyken, J. Ge, S. Mahadevan, and C. DeWitt, "First Planet Confirmation with a Dispersed Fixed-Delay Interferometer," *ApJ* **600**, pp. L79–L82, 2004.
17. J. C. Van Eyken, J. Ge, X. Wan, B. Zhao, A. Hariharan, S. Mahadevan, C. DeWitt, P. Guo, R. Cohen, S. W. Fleming, J. Crepp, C. Warner, S. Kane, F. Leger, and K. Pan, "Latest Results from the Multi-Object Keck Exoplanet Tracker," in *American Astronomical Society Meeting Abstracts*, Dec. 2006.
18. J. C. Wilson, C. P. Henderson, T. L. Herter, K. Matthews, M. F. Skrutskie, J. D. Adams, D.-S. Moon, R. Smith, N. Gautier, M. Ressler, B. T. Soifer, S. Lin, J. Howard, J. LaMarr, T. M. Stolberg, and J. Zink, "Mass producing an efficient NIR spectrograph," in *Ground-based Instr. for Astr., Ed. A. Moorwood & I. Masanori.*, *SPIE Proc.* **5492**, pp. 1295–1305, 2004.
19. NOAO webpage September, 2006. http://www.noao.edu/noaoprop/help/etmemo.html.
20. P. Connes, "Absolute Astronomical Accelerometry," *Astrph. & Spc. Sci.* **110**, p. 211, 1985.
21. J. Harlander, R. Reynolds, and F. Roesler, "Spatial Heterodyne Spectroscopy for the Exploration of Diffuse Interstellar Emission Lines at Far-ultraviolet Wavelengths," *ApJ* **396**, p. 730, 1992.
22. G. W. Marcy and R. P. Butler, "Detection of Extrasolar Giant Planets," *ARA&A* **36**, pp. 57–98, 1998.