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Spectroscopy with the Terrestrial Planet Finder Coronagraph

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Abstract. We describe the rationale and requirements for an integral-field spectrograph aboard NASA's Terrestrial Planet Finder Coronagraph.

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1. Introduction

Ten years from now, we should be familiar with planetary systems around nearby stars. Radial-velocity monitors will have identified those systems having giant planets in Jupiter-like orbits. Corot and Kepler will have discovered rocky planets transiting their parent stars, and NASA's Space Interferometry Mission will have discovered systems having massive terrestrial planets orbiting nearby stars. The prime targets for follow-up characterization are planets orbiting bright, nearby stars found by Doppler techniques and SIM interferometry. These techniques, however, are indirect: their evidence for planets comes from measurements of the orbital motions of the host stars. NASA is therefore planning a mission called the Terrestrial Planet Finder Coronagraph (TPF-C) that will enable us to detect and analyze light from an earth-like planet itself. Its light can tell us about the physical conditions on the planet, whether the planet is habitable, and perhaps even if the planet has life. TPF-C's prime instrument for analyzing light is a spectrograph that will be used to simultaneously characterize all planets, gas and dust within the coronagraphic field.

2. Instrument Concept

NASA recently selected us to study a coronagraphic spectrograph (CorSpec for short) for TPF-C. We envision a spectrograph with four optical channels operating simultaneously. Together, the four channels cover the spectral range, 0.45–1.10 microns. Each channel is fed by a starlight suppression system optimized for the wavelength region of that channel. Each channel has its own integral field unit (IFU) sampling a 140 × 140-spaxel field, a set of dispersers (prisms and grating), and a photon-counting detector system optimized for that passband, which is about 22% wide.

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Each of the four starlight suppression systems should produce a high-quality coronagraphic image in the central wavelength region of the passband, but the flanking wavelength regions may be corrupted by bright speckles produced by phase and amplitude wavefront errors. We therefore envision a wavefront-sensing system that uses the short- and long-wavelength flanks of all four optical channels to detect changes in the wavefront, to diagnose the wavefront, and to send back instructions for correcting the wavefront in each of the four starlight suppression systems.

The wavelength of transition between adjacent channels can be adjusted by selection of the appropriate dichroic beamsplitter that intercepts light from the telescope before entering the starlight suppression systems. We expect that two exposures, each employing its own set of dichroic beamsplitters, will be sufficient to cover the full spectral range of CorSpec without gaps.

3. Scientific Objectives

One of the primary objectives of TPF-C is to characterize … terrestrial planets spectroscopically, searching for absorption caused by O_2, O_3, H_2O, and possibly CO_2 and CH_4. The ability to measure Rayleigh scattering and photosynthetic pigments is also desired. Such information may provide evidence of habitability and of life itself. By definition, a potentially habitable planet is a terrestrial planet lying within the Habitable Zone, the annulus around a star where H_2O would be in its liquid state (Des Marais *et al.* 2001). The inner and outer radii of the HZ are approximately $0.7\sqrt{L_{\mathrm{bol}}}$ and $1.5\sqrt{L_{\mathrm{bol}}}$ AU.

The science objectives combined with the intrinsic and observed properties of the target stars dictate the performance requirements of CorSpec. We therefore compiled a plausible TPF-C target list composed of sun-like stars having no companion within 8". Most are metal-rich, which makes them among the most likely to have planets (Valenti & Fischer 2005; Santos *et al.* 2005; Fischer & Valenti 2005), although there is a healthy diversity in metallicity. For example, we should get a good clue to the influence on metallicity on the formation of planets by comparing the disk around τ Ceti ([Fe/H] $= -0.52$) with that of ϵ Eri ([Fe/H] $= -0.03$). Although the estimated ages have very large uncertainties, most appear to be older than a billion years, so the chances of life having started are higher (if the Earth is a good example), and the background presented by their exo-zodiacal disks should be fainter (Habing *et al.* 2001).

Figure 1-Left plots the separation of Earth-like planets at the inner edge of the Habitable Zone (IHZ) at quadrature (circular orbits assumed) vs. the visual magnitudes. It shows that the HZ of all the targets lie outside TPF-C's Inner Working Angle for Detection, $\mathrm{IWA_D}$=62 mas, at 6000 Å (The IWA scales with wavelength.) Except for α Cen, their angular separations from the star are less than 360 mas at the outer edge of the habitability zone (OHZ). All have planet-star brightness ratios in the range from 0.8×10^{-10} (F stars) to 17×10^{-10} (K stars) at the IHZ. At the OHZ, however, some planet-star brightness ratios are as low as 0.2×10^{-10}, well below TPF-C's nominal capabilities of 1×10^{-10}. The faintest planets have V=30.3 at the IHZ and V=31.9 at the OHZ.

Not only are Earth-like planets faint sources, but they are seen close to stars that can be 10 billion (10^{10}) or more times brighter. Figure 1-Right illustrates the stellar-glare challenge for a prime TPF-C target, 47 UMa, which is known to have two outer giant planets in near-circular orbits (Fischer *et al.* 2002). If a potentially habitable planet has only half the surface area of the Earth ($M = 0.35M_{\oplus}$) and lies in the outer edge of the Habitable Zone, CorSpec may have to characterize planets with planet-star brightness

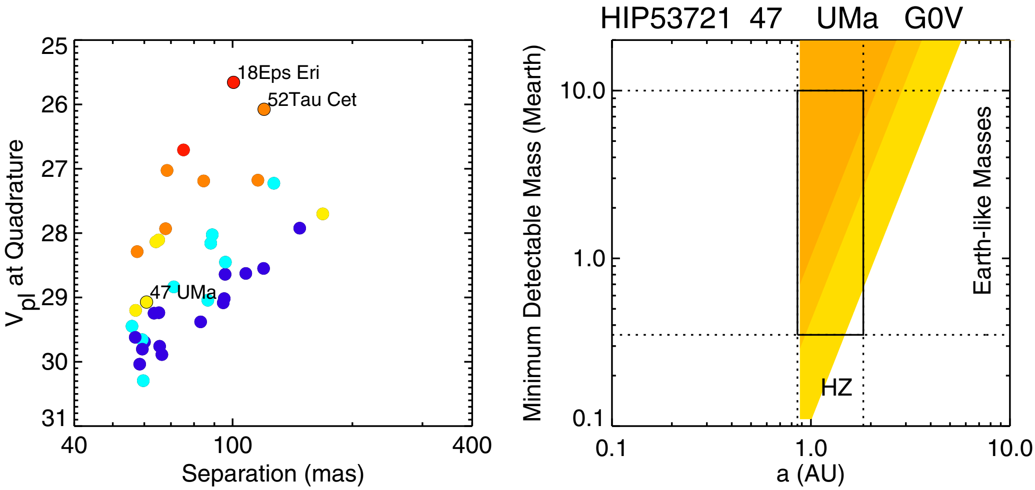

Figure 1. Properties of target stars. Left: Visual magnitude and angular separation of Earth-like planets at the IHZ as seen at quadrature. Right: Coverage of the HZ for three different contrasts, $L_p/L_s = 2, 1,$ and 0.4×10^{-10} (dark to light shades).

ratios less than $L_p/L_s = 0.4 \times 10^{-10}$. This brightness ratio is lower than the nominal capabilities of TPF-C, 1×10^{-10}.

4. Performance Requirements

Sensitivity. The faintness of terrestrial planets puts severe demands on the CorSpec detectors. The main problem is read noise from the CCD detector ($3e^-$), which – because it must be read out every 1000 seconds to limit the build-up of cosmic-ray hits – is usually much stronger than the planet flux. Only with a photon-counting detector can we obtain spectra of planets orbiting all of TPF-C's core stars.

Efficiency. Even with a photon-counting detector, a typical exposure take days to obtain with the standard starlight suppression system; and as noted above, two exposures are required to cover the full spectral range without gaps. We are therefore working to design special masks for spectroscopy that would further shorten the time. The standard system employs masks suited for search and discovery but only probes to 62 mas at 6000 Å and is proportionately larger at longer wavelengths. The spectroscopic masks would cover only a small portion of the coronagraphic field but would probe in to half that separation, so that we could observe a planet at gibbous phase (rather than at maximum elongation) when it would be a full magnitude brighter. A 2.5 X increase in brightness translates to a 5 X reduction in exposure time needed to reach the same signal to noise ratio. Counteracting this gain is the loss in overall throughput by the spectroscopic masks, so the actual gain will be less. However, independent of the throughput question, is the gain in terms of contrast: with the spectroscopic masks, the brightness of a planet is increased by a factor of 2.5 X with respect to the speckle background.

Spatial Multiplexing. Since the exposure time for an observation takes days or even weeks, and the wavefront-corrected spectral band may be only 0.1μ wide, it is imperative to maximize CorSpec's efficiency. An integral field spectrograph (IFS) can provide that high degree of multiplexing efficiency by simultaneously obtaining a spectrum of each image element in the coronagraphic field – and do so without having had to acquire the target in some slit or orient the telescope at a specific roll angle.

CorSpec will need to Nyquist-sample $\geqslant$90% of the entire Habitable Zone around "core stars" at the TPF-C angular resolution, to disperse the light of each sample for a resolving power of 70, and to record the 2×10^4 spectra with just one detector per channel. The table below gives the implied optical parameters of the IFU, evaluated at 0.5 and 0.8 microns.

Optical Parameters of the CorSpec IFU

Parameter	0.5μ	0.8μ
Inner Working Angle (mas)	52	83
Outer Working Angle (mas)	620	990
Angular resolution (mas)	18.4	29.5
Angular sample size (mas)	9.2	14.7
Samples across the FOV	134	134

Wavefront Sensing. The TPF-C Starlight Suppression System (SSS) is currently thought to be operated in a "set and forget" mode. It is therefore limited by changes in the telescope wavefront during an observation. However, we cannot expect the Starlight Suppression System to remain stable over the days needed to obtain a spectrum of a terrestrial planet. We therefore plan to use CorSpec to monitor the wavefront while an observation is being made, diagnose changes in wavefront, and send instructions for correction back to the Starlight Suppression System.

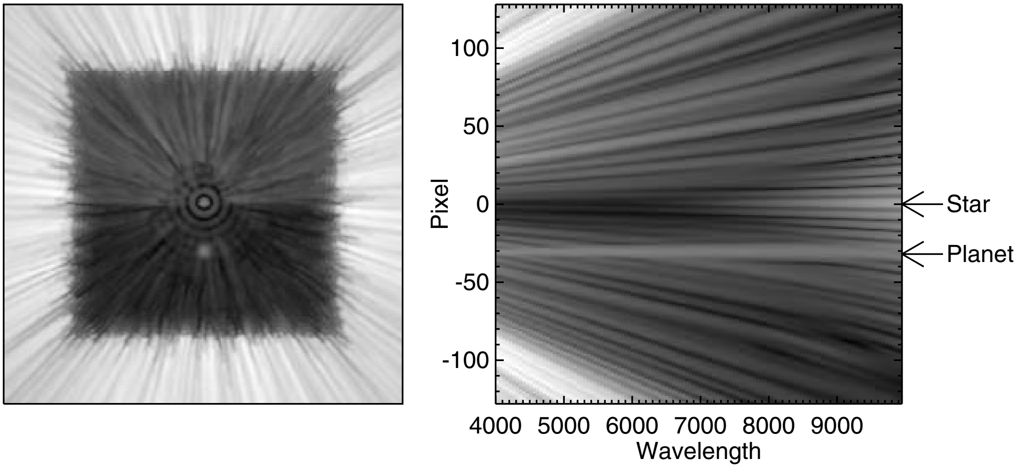

Figure 2. Simulated cross-cuts of a TPF-C datacube. Left: A wide-band image reconstructed from a swath of monochromatic images in the datacube. Right: A cross-cut at x_p showing the divergence of the background "speckles" with increasing wavelength. Note the edge of the dark hole at short wavelengths, and stellar leakage around the mask at long wavelengths.

5. CorSpec Data

The datacube (x, y, λ) produced by an IFS observation is rich in information. Not only can the datacube be manipulated to yield the background-subtracted spectrum of a planet that can be examined for biomarkers (Des Marais *et al.* 2001), but it can be reformatted into a wide-band image for planet detection (Fig. 2-Left). It can also be reformatted into a set of narrow-band images to show the distribution and chemistry of gas in disks during the late stages of planet formation (Brandeker *et al.* 2004). Quantities of gas as small as one Earth mass may be crucial to forming terrestrial planets by causing them to migrate, damping their eccentricities, altering their formation mechanisms, and supplying them with proto-atmospheres and essential volatiles.

A crosscut of the datacube at a specific x or y produces a pseudo-long-slit spectrum showing how artifacts of wavefront errors ("speckles") change in position and brightness with wavelength (Figure 2-Right). Such information will be invaluable for modeling and removing the speckle background. It will also be invaluable to the wavefront-correction system on-board TPF-C.

In summary, an IFU is the ideal device for coronagraphic spectroscopy, and a coronagraphic spectrograph in space is an ideal application for an IFU. The main design challenge is how to pack about 20,000 spectra onto one $2K \times 4K$ photon-counting CCD without serious cross-talk between adjacent spectra.

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All photographs: Laurent Thareau [`l.thareau@free.fr`].