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Science Capabilities of the ST3 Mission

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Abstract. The ST3 mission will launch a space optical interferometer into heliocentric orbit, for observation of 50–100 sources on baselines of 40–200 m. The detection threshold will be visual magnitude 8–10, and the angular resolution in the 450–900 nm passband will be ≈ 500 microarcseconds. Interesting science targets which could be imaged include: Wolf-Rayet stars, Be stars, and M dwarfs.

1. Introduction

The ST3 mission will place two spacecraft into heliocentric orbit to do optical interferometry (450–900 nm band). With a fixed delay line on one spacecraft (the 'combiner'), zero total delay can be achieved by placing the second spacecraft on the surface of a parabaloid, whose axis points towards the target star. For a fixed delay line of length τ_{fixed}, the relation between the y-coordinate (along the axis of the parabaloid) and the projected baseline length B is:

$$y = \frac{B^2}{2\tau_{\text{fixed}}} - \frac{\tau_{\text{fixed}}}{2} \tag{1}$$

With a 20 m fixed delay line, and a maximum allowed range between spacecraft of 1000 m, ST3 can achieve projected baselines up to 200 m in length. The minimum projected baseline length will be 40 m—the two spacecraft must remain ≥ 50 m apart for safety reasons. Each spacecraft will have a 12 cm diameter siderostat to capture starlight.

Operating above the earth's atmosphere allows a big improvement in sensitivity over ground-based optical interferometers. Rapid atmospheric delay fluctuations limit the coherence time of a ground interferometer to a few milliseconds. For a space interferometer, almost all the power in delay fluctuations will occur at frequencies $<< 1$ Hz. For ST3, we expect that low power thruster firings ($\sim 100\ \mu$N s), at intervals of several hundred to several thousand seconds, plus a small, constant acceleration from solar radiation pressure, will be the only significant disturbances to the spacecraft motions. As a result, the coherence time will be $>> 1$ s. Once fringes are detected, coherent integration for many seconds can be used to achieve a high signal-to-noise ratio, even on weak sources.

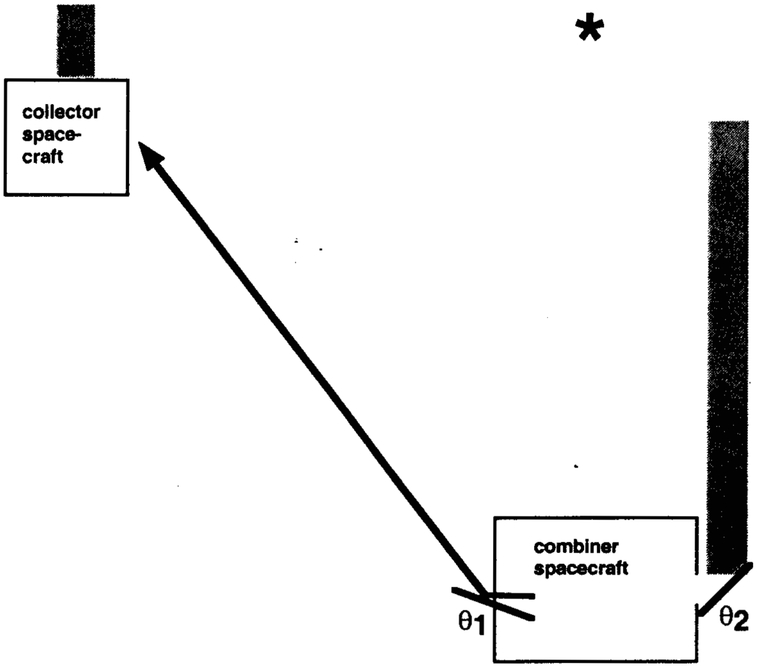

Figure 1. Geometry of ST3, showing the starlight beams (broad gray) and the laser metrology beam (black arrow). The angles θ_1 and θ_2 are used to estimate the interferometer delay. The star is in the vertical direction.

The challenge is to detect fringes in the first place, and this process will be limited primarily by the uncertainty in the interferometer delay rate. With one or two guide interferometers (such as with SIM), the delay rate will be accurately known, but ST3 will not have this capability. The delay rate knowledge will be derived from a time series of angle measurements, as illustrated in Figure 1. The value of the combiner siderostat angle (θ_2), when the gimbal is adjusted to align the starlight beam with the optical axis of the combiner, yields the combiner spacecraft attitude. The metrology steering mirror will be adjusted to center the outgoing laser metrology beam on a sensor on the collector spacecraft. The angle (θ_1) of the mirror gimbal then yields (in combination with θ_2), the orientation of the separation vector between the two spacecraft. The time derivatives ($\dot{\theta}_1$ and $\dot{\theta}_2$), in combination with the range rate from linear laser metrology (and an absolute range from formation flying RF measurements), yield the delay rate.

This method of delay rate estimation will be applicable to the Terrestrial Planet Finder (TPF) mission. In its astrophysics mode (as opposed to planet search mode), many targets will be so weak that a guide interferometer will be needed. The brightest guide star in a typical field of view will be 18th magnitude at the 2.2 μm wavelength used for fringe search and tracking. Figure 2 quantifies the delay rate knowledge requirements for fringe-searching with ST3 and TPF. Frinding fringes with TPF will require delay rate knowledge 4–5 times better

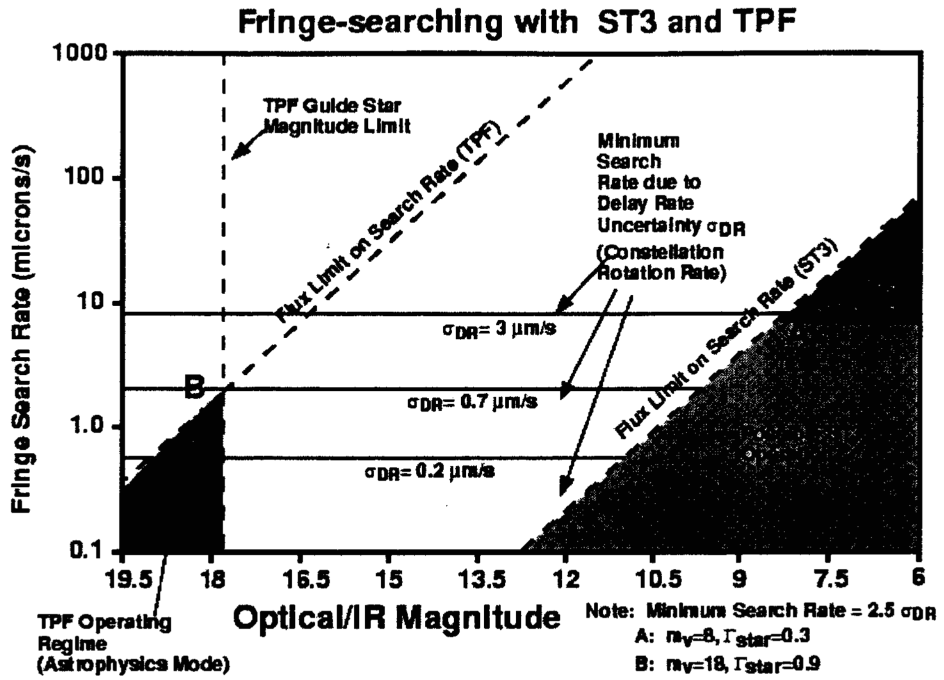

Figure 2. The translation between delay rate knowledge and fringe detection capability for ST3 and TPF. Note that the requirements for TPF are 4-5 times more stringent in delay rate, or ≈ 25 times more stringent in angular rate measurements.

than is needed for the ST3 design point ($V = 8$ and $\Gamma_{\rm star} = 0.3$). Because the maximum TPF baseline will be ≈ 1000 m (five times longer than for ST3), the required angle rate sensing accuracy will be ~ 25 times more stringent for TPF than for ST3.

2. Science Capabilities

Aperture synthesis with ST3 will involve moving the two spacecraft, in order to change the vector baseline. During the planned science phase of 3–4.5 months, 50–100 sources can be observed (this estimate assumes that a simple one-dimensional u-v coverage will be used for most sources, with more detailed two-dimensional coverage for a limited subset of sources).

The fringe phase can be measured during ST3 observations. However, the uncertainty in the geometric delay (0.2–2 cm) results in thousands of cycles of uncertainty in the geometric component of the fringe phase. The structure (visibility) phase will therefore be completely unknown, and only the visibility amplitude can be measured, in general. (For Wolf-Rayet stars and Be stars, phase referencing will allow measurement of structure phase in the emission lines, relative to that of the stellar photosphere). ST3 will be restricted to simple

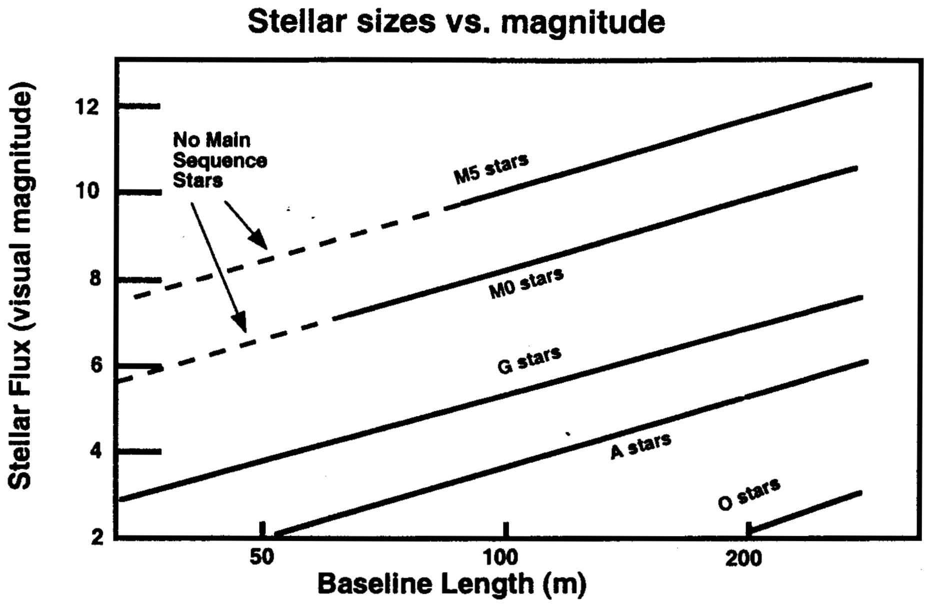

Figure 3. The visual magnitude *vs.* baseline length for stars of various spectral types. The plotted lines are for a stellar visibility $\Gamma_{\rm star} = 0.7$

source structure measurements, generally derived from model fitting instead of a true inversion of the visibility data.

The expected ('design point') detection limit for ST3 will be a visual magnitude $V = 8$ for sources with visibility $\Gamma_{\rm star} = 0.3$. For $\Gamma_{\rm star} = 0.7$ (adequate for measuring the angular sizes of simple sources), the limit will be 1.5 magnitudes fainter. For M stars, where most of the flux is at wavelengths longer than in the V band, the detection limit (in V) will be 1.5 magnitudes fainter than for hotter (B through G) stars. Thus an M star as faint as $V = 11$ may be detectable for $\Gamma_{\rm star} = 0.7$.

Figure 3 shows the baseline lengths needed to resolve stars, as a function of spectral type and visual magnitude. ST3 will be able to resolve the brightest A and B stars, and M stars down to the detection limit.

3. Science Targets of Interest

The science capabilities of ST3 (40–200 m baselines, detection limit of $V = 8$–10), are comparable to those anticipated for several ground-based interferometers (*e.g.* NPOI, CHARA) at the time of ST3's launch. Therefore, we are not able to identify any ST3 observations which *definitely* cannot be made from the ground

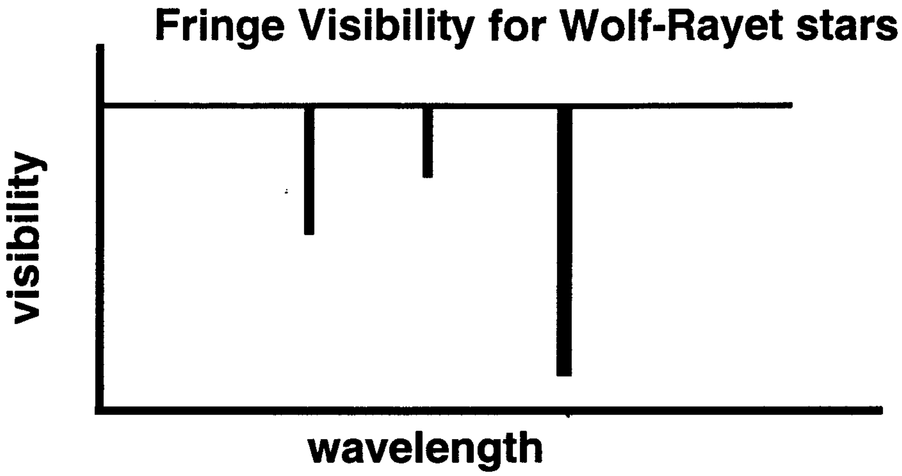

Figure 4. A cartoon of the fringe visibility *vs.* wavelength for a Wolf-Rayet star. The outflow will have high opacity in a few strong spectral lines, leading to low fringe visibility.

(ST3 is primarily a technology demonstration mission). However, we have identified three types of objects for which ST3 observations could yield interesting new science, beyond that possible with current ground-based interferometers.

3.1. Wolf-Rayet stars

Wolf-Rayet stars (Abbott & Conti 1987) are hot (effective temperature $\sim 30,000$ K), with very strong outflows (10^{-5}–10^{-4} $M_\odot$/yr). In the continuum, ST3 will see the stellar surface, which will be compact and unresolved. This continuum emission can be used for the detection and tracking of fringes. A few of the strongest emission lines have widths comparable to the ST3 channel width of 1/80 octave ($\sim$ 4000 km/s), so that the measured visibility as a function of wavelength will look something like the plot in Figure 4.

In this case, the (presumably) unresolved continuum can serve as a phase reference, allowing measurements of both the visibility amplitude ***and phase*** in the strong emission lines. As a generalization for simple outflow shapes, the visibility amplitude can be used to derive the radial density profile and aspect ratio (flattening) of the outflow. The visibility phase will be sensitive to any asymmetry (*i.e.* whether the outflow is stronger on one side of the star than the other).

3.2. Be stars

Be stars (Slettebak 1988) have emission lines, originating from material beyond the stellar photosphere. The strategy for imaging this circumstellar material (which is thought to be concentrated in the star's equatorial plane, forming a disk-like structure) will therefore be similar to that for Wolf-Rayet stars.

However, there will be an important difference, due to the fact that the widths of Be-star emission lines are a few hundred km/s, much narrower than the width of a CCD spectral channel on ST3. Furthermore, a spectral resolution several times finer than the total Be star line width is desired, in order to study the dynamics of the circumstellar material. Therefore, we plan to operate ST3 in a Fourier Transform Spectrometer mode for Be star observations.

In this mode, fringe-searching will be done in the same way as for other stars. Once fringes are found, the delay line will be swept back and forth, over a range as large as 2000–3000 μm. The detected signal (amplitude and phase) *vs.* delay, in each CCD spectral channel, will be Fourier Transformed to yield the correlated flux (and phase) *vs.* wavelength. This can be divided by the total spectral intensity (from ground-based photometry) to derive the complex visibility. The TPF project hopes to include this observing mode in their mission; a successful demonstration by ST3 would be valuable. A preliminary analysis suggests that stars as faint as $V \approx 5$ can observed by ST3 with a velocity resolution of $\approx$ 70 km/s.

One specific question on Be stars to be addressed by ST3 observations concerns the presence or absence of a gap between the photosphere and the inner edge of the disk. The answer is important for understanding the formation mechanism of the disks in these objects.

3.3. M Dwarfs

The effective temperature scale of the lower main sequence is poorly known. The spectra of M stars deviate strongly from a blackbody curve, so the connection between spectra and effective temperature is not simple. Current ground-based interferometers can measure the angular sizes of M giants and supergiants, but not M dwarfs.

ST3 measurements of the angular sizes to an accuracy of 2.5% would allow effective temperature determinations to $\approx$ 5%, a factor of $\sim$ 4 better than current knowledge. For visibilities in the range 0.5–0.7, a visibility calibration accuracy of $\Delta\Gamma_{\rm star} \approx 0.02$ is needed to achieve a size accuracy of 2.5%. The sensitivity of ST3 should allow M dwarfs as cool as $\approx$M6 to be observed.

References

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Slettebak, A. 1988, PASP, 100, 770