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Letter to the Editor

Hubble space telescope astrometric observations of pre-main sequence stars from the HIPPARCOS program

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Abstract. We report on the first set of high angular resolution observations with Fine Guidance Sensor (FGS) # 3 aboard the Hubble Space Telescope of a sample of T-Tauri and Herbig Ae/Be pre-main sequence stars, which have also been observed with the HIPPARCOS satellite. Among the 5 Ae/Be stars observed so far of particular interest is the new double HIC 35488 the first close *visual* pair in this class of stars and possibly a candidate *orbital* binary. Repeated FGS astrometry combined with the parallaxes provided by HIPPARCOS could yield the first direct determination of the mass of an Ae/Be type pre-main sequence system.

Finally, the timely availability of these FGS measurements will help the validation of the algorithms applied to the HIPPARCOS data to detect and possibly measure close pairs.

Key words: Astrometry – Stars: pre-main-sequence stars – Stars:binaries: visual

1. Scientific background

During Cycle 2 and 3 of the Hubble Space Telescope program we are observing with the Fine Guidance Sensor No. 3 (FGS3) 18 pre-main sequence stars (PMS) (selected from Herbig and Rao 1972; Finkenzeller and Mundt 1984; and Baier et al. 1985) which are on the HIPPARCOS Input Catalogue (HIC) of the ESA astrometry satellite (Turon et al. 1992). Among these, 7 are T Tauri stars and 11 are Herbig Ae/Be objects (HAEBE). Purposes of the investigation are:

(a) to detect new binaries in the sample with separations below the detection limit of HIPPARCOS ($0.1''$) and down to $0.01''$.

This is relevant to the assessment of the frequency of PMS binaries nearer than 200 *pc* having physical dimensions similar to those of a planetary system. Recent investigations have unveiled 9 double systems in the separation range $0.01''$ to $0.5''$ by means of lunar occultations in the Taurus and Ophiucus star forming regions (Chen et al. 1990, Simon et al. 1987). Among "wide" PMS binaries (separations larger than around $2''$) the frequency of duplicity has reached 46% and extrapolations to 70% have been proposed (see McAlister and Hartkopf Eds.). Discovery of planetary sized PMS's will help in placing observational constraints on models of disk formation around newly born stars. Models of PMS binaries can be further constrained by observing a wide range of protostar masses, namely T-Tauri stars (0.5-2 $M_\odot$) and HAEBE stars (2-7 $M_\odot$).

(b) to possibly determine the orbits, hence the masses of those pre–main sequence objects found to be angularly close binaries.

The satellite HIPPARCOS is providing parallaxes with accuracies in the range $0.0013''$ to $0.002''$ for magnitudes B=9 to B=12. At the level of 20% accuracies the parallax precision sets the limiting distances to 160 *pc* and 100 *pc* leading to a precision for mass determination of 60%. However in the case of stellar complexes like the Tau/Aur region (150 *pc* away), mean parallaxes can be derived by combining the individual proper motions of all the HIPPARCOS stars in each region. In the end, in the case of the Taurus region, only the intrinsic dimension of the complex (nearly 12 *pc*) will, in practice, contribute to the error on the distance which translates to $\sim 25\%$ accuracy on the derived masses. Better accuracies shall wait for microsecond astrometry.

In the present letter we report on the results obtained so far on five Herbig stars (Table 1).

2. FGS observations and measurements

All exposures executed for this program use the TRANS mode capability of FGS#3 (called the *astrometer* FGS). As described in the FGS Instrument Handbook (Taff and Lattanzi 1990) this mode samples the interference pattern produced by the Koester's prism interferometer in the FGS (Kovalevsky 1990; L.G. Taff 1991). There are actually two such interferometers,

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Table 1. *Ae/Be* stars observed with FGS#3.

ID (HIC)	V $(B-V)$	Sp	Observing Times
BD +06°1154 3401	$11.2 \div 12.3$ -0.31	Be	1992.984
HD 250550 28582	9.50 $+0.084$	A0	1992.989
CD−44°3318 35488	$10.0 \div 11.3$ $+0.15$	A6IIIe	1993.000
GG Car 53444	9.46 -0.31	Be	1993.123
BD+41°3731 100628	9.89 0.13	B3n	1993.118

one for each FGS axis, which are usually referred to as X– and Y–axis. When a TRANS mode observation is executed, the FGS instantaneous field–of–view (FOV) scans across the target (with a commandable angular step size) at a fixed 45° angle to the X and Y axes. The result is the aforementioned X and Y interferometric patterns. On each axis there is a pair of photomultipliers (denoted by channels A and B). The counts are analyzed in the form of a normalized visibility curve (or fringe)

$$S = (C_A - C_B)/(C_A + C_B), \qquad (1)$$

where C_A and C_B are the counts from the two channels per axis. Eq.(1) is often referred to as FGS *transfer function* (TF) or, simply, *S–curve.*

All observed fringes were $\simeq 1.7''$ in length and sampled with an angular step size of $\simeq 0.8$ *mas*. The yellow F550W filter ($\lambda_{eff} = 550$ nm, FWHM = 75 nm) was always in place to minimize the effect of residual chromatic aberration within the FGS and to enhance the stellar component from the redder spectrum of the complex nebulosities which are part of our objects. Between 8 and 10 of such scans were executed on each target.

Thanks to these multiple scans, the resulting Signal-to-Noise ratio (S/N) of the co–added S–curves used is always > 30.

The flaw in the HST main optics and residual aberrations and misalignments within the FGS itself are producing field dependent effects across the FOV of the unit. Even at the center of the FOV (all our observations were taken as close as possible to this location) the actual TF [defined in Eq.(1)] is different from the theoretical one that can be computed analytically from the application of first principles to Koester's prism-based interference. Thus, to determine the signature of a single star (SS) one must resort to in-flight calibrations. Routine observations of the standard SS Upgren 69 (V=9.55) (Upgren et al. 1972) are scheduled by the ST ScI as part of the FGS calibration plan. These calibrations lack observations through the F550W filter. We then devoted one orbit of the time allocated to take 10 scans of Upgren 69. These scans were in everything similar to those on the program stars. In Fig.1 we show the co–added X– and Y–axis fringes of our reference SS transfer function.

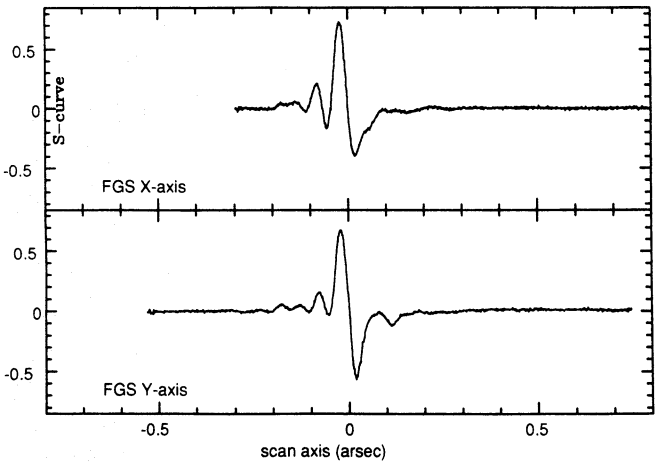

Fig. 1. F550W S–curves of standard single star Upgren 69.

The algorithm for the measurement of double stars is based on the comparison, via cross-correlation, of the observed fringes with high S/N templates built from scans of certified single stars like the Upgren 69 template shown in Fig. 1 (Bucciarelli et al. 1991; Franz et al. 1992; Lattanzi et al. 1993). This makes it possible to detect and measure separations well below the nominal HST resolution limit (of about 0.06″ at 550 nm). Early results based on the above technique (Franz et al. 1991; Lattanzi et al. 1992; see also references above) indicate that the FGS interferometers are capable of measuring separations good to 30% and position angles to better than 1° at 10 *mas* which appears to be the resolution limit.

Briefly, assume we know the form of the SS TF $[S(X)]$. The hypothesis that the incoming light from two different sources, close by in the sky, is incoherent and the application of the superposition principle yield the expected Double Star (DS) TF $[D(X)]$ in the form of a linear combination of two SS TFs, i.e.,

$$D(X) = A(\Delta m)[S(X) + B(\Delta m)S(X + dX)] \qquad (2)$$

(and its analogue for the Y–axis), where the second SS TF $[S(X + dX)]$ is identical to the first but displaced along the X–axis by dX, the DS projected separation. $A(\Delta m)$ is a normalization factor, and B is the intensity ratio of the primary to the secondary star. Both quantities are, of course, functions of the primary/secondary magnitude difference (Δm). The model just described is fitted to the observed TF curve and the parameters dX and Δm derived. It is worth noticing here that two independent estimates of Δm are available, one for each FGS axis. In practice, a grid of models is generated by varying dX and Δm. Each DS model is cross-correlated wih the observed TF and the best–fit model chosen. On–sky separation (ρ) and position angle (θ) are then computed from

$$\rho^2 = dX^2 + dY^2, \qquad \theta = tan^{-1}(dY/dX) + \theta_0. \qquad (3)$$

The offset θ_0 depends on the orientation of the scan to the direction of the North Celestial Pole and is computed from the spacecraft attitude parameters at the time of observation.

3. Results and discussion

The grids of synthetic "doubles" [Eq.(2)] for the correlation runs were generated with an angular step of $(dX$ or $dY) =$ 5 *mas* and a Δm step of $0.^{m}07$. In all cases we have used the co–added scans for best resolution. The correlation steps must be chosen such that the numerical procedure yields the best results possible for the S/N of the scans utilzed with a minimum of calculations. The bins adopted here are optimal in the sense that finer steps would improve the results only artificially . The actual accuracy is set by the noise sources in the transfer functions. More on the characterization of the error in the measurement of FGS scans is given in Lattanzi et al (1992). The results of the FGS measurements are summarized in Table 2. A separation $<$ 10 *mas* there means that the projected separations measured (one for each FGS axis) are less than two times the resolution of the best fit procedure (±5 *mas*).

HIC 35488 has been resolved as double. It is a new double and the closest *visual* pair to date among HAEBE stars. As such, it is the best candidate for the first astrometric binary in its class, which would lead to the first astrometric mass determination of an HAEBE PMS object. The FGS X– and Y–axis co–added fringes of this new double are shown in Fig. 2. The corresponding synthetic S-curves computed from Eq.(2) and the best fit parameters listed in table 2 are also shown. For clarity, the best fit models are artificially shifted by +0.1 units along the ordinate axis. It is interesting to note here the very good agreement of the two independent determinations (one for each FGS axis) of the magnitude difference Δm. The best fit values are 0.63 ± 0.07 *mag* and 0.65 ± 0.07 *mag* for the interferometer X– and Y–axis respectively.

PMS stars are often multiple systems. Actually, the multiplicity frequency among young stars seems to exceed that of the solarlike stars (Simon 1992). Following the prescriptions that led to Eq.(2), building a three–component (or more) synthetic multiple star is simple. Thus we could try to fit a more complicated model to the observed fringes. Inspection of the fringe residuals for HIC 35488, obtained by subtracting the best correlation synthetic models to the observed fringes both depicted in Fig.2, show that there is no need for a third component (less than 2.5 *mag* fainter than the primary component) in our synthetic S-curves.

Table 2. Results of FGS measurements.

HIC	3401	28582	35488	53444	100628
$\rho(arcsec)$	< 0.01	< 0.01	+0.126 ±0.007	*dubious*	< 0.01
$\theta(deg)$			63.4 ±1.0		
$\Delta m(mag)$			0.64 ±0.07		

HIC stars 53444 (GG Car) is a dubious case. This is a candidate eclipsing binary with a period of 62 days (Gosset et al. 1984). We were expecting a V flux corresponding to magnitudes between 9^m and 10^m (i.e. close enough to our V=9.55 template). Our own estimate based on the counts from the FGS photomultipliers indicates that the object is about 5 magnitudes fainter than expected. This is too large a difference (the 62-day variability of GG Car lightcurve is only 0.5 *mag*, Gosset et al. 1984) to argue for any reasonable explanation. At the moment we are investigating an FGS acquisition error. An identification chart of the field shows a spoiler star of the right magnitude some 18″ S–E of GG Car. Hopefully, we will have the opportunity to reobserve this target. For, it would be very important to see if the FGS can actually resolve this object in two stellar components. A positive detection would require a close monitoring of the object with the FGS. A confirmation that the 62-day period is associated with a two-star orbital motion would for example discount that of a ring of material or other formations (rather common in these complex objects).

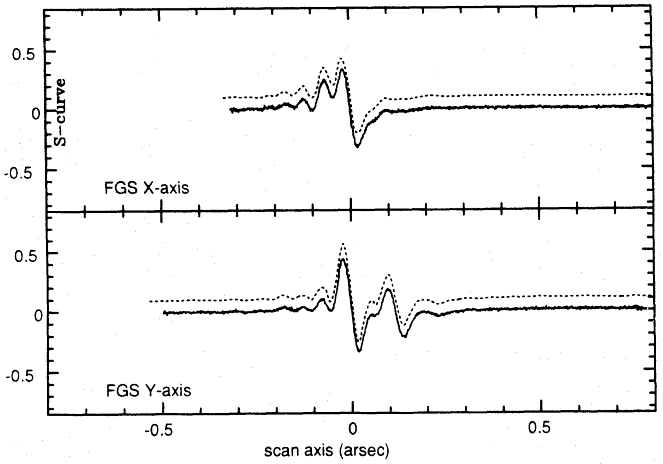

Fig. 2. The orbital binary candidate HIC 35488. The best correlation synthetic models (dotted lines) are displaced for clarity. The projected separations are -0.039″ ± 0.005″ along the astrometer X–axis, and 0.120″ ± 0.005″ in the direction of the Y–axis.

Confirming GG Car as a relatively short period *resolved* binary would lead to one more rather interesting speculation. If we calculate the mass of the system from standard tables (Schmidt-Kaler 1982) and the data in Table 1, and we further assume that the FGS detects a separation of $\sim$ 0.01″, then Kepler's second law gives a distance $\leq$ 100 *pc*, a factor of ten smaller than the spectroscopic distance derived from the same tabular data. This is a prediction that HIPPARCOS can easily validate once its definitive parallaxes become available.

HIPPARCOS data are particularly valuable for the new double HIC 35488. Although its separation is close to the detection limit of the satellite, preliminary results indicate that for separations in the range 0.1″ ÷ 0.2″ a solution for the basic double star parameters (ρ, θ, and Δm) can be attempted (Mignard et al. 1992). The photometric variability of the star is a further complication in the data reduction but it can be dealt with, for example, with the algorithms proposed by Pannunzio et al. (1992). Upon availability of a consistent set of validated satellite data we will attempt a double star solution for HIC 35488. As HIPPARCOS has been observing since December 1989, the comparison of results based solely on satellite data with the FGS findings presented here could reveal an orbital period of a few years.

Given the angular separation of the two components in HIC 35488, if we repeat the same exercise we went through before for GG Car, the expected orbital period (assuming the physical association of the components) exceeds 150 years. Thus, if the HIPPARCOS/FGS comparison does show significant orbital motion, we would predict a much shorter distance to the star. Once again, this prediction can be easily validated once the HIPPARCOS parallax for this system becomes available. Reduced distances would imply that Herbig Ae/Be PMS are significantly less luminous than normal stars of similar spectral type, or that there is anomalous extinction toward these objects, or a combination of the two.

Finally, we like to mention that the FGS results presented in this paper, thanks to their high quality, will be used as *benchmark* data for testing the reliability of the algorithms developed by the two HIPPARCOS data reduction consortia to detect and measure close doubles in the $0.1'' \div 0.2''$ separation range (see Perryman et al. 1989 for a complete review of double and multiple star reduction methods with HIPPARCOS data).

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