THE ASTROPHYSICAL JOURNAL, 479:L47–L50, 1997 April 10

DIPPING ACTIVITY IN THE X-RAY PULSAR 4U 1907+09

J. J. M. IN 'T ZAND,[1] T. E. STROHMAYER,[2] AND A. BAYKAL[3]
Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771
Received 1996 August 30; accepted 1997 January 27

ABSTRACT

New observations of 4U 1907+09 with the *Rossi X-Ray Timing Explorer* show a kind of behavior never recognized before from this X-ray pulsar: intermittently, the X-ray intensity fades below the detection threshold during intervals ranging from a few minutes to perhaps 1.5 hours. The largest decrease of the 2–15 keV intensity is at least 98%. The observations span 70% of the orbit of the binary system of which the pulsar is a part. The dips were found to have a broad range of orbital phases. Given the strong variability of the source outside the dip periods with moderate changes in the spectrum, the occasional variable weak emission during dip periods with timescales and spectrum similar to that outside the dip periods, and the absence of strong enhancements in the column density of cold circumstellar matter (i.e., N_H remains below 10^{23} cm^{-2}), it is suggested that the dips are caused by cessations of the mass accretion by the neutron star rather than occultations by circumstellar gas. An inhomogeneous wind from the companion star may be responsible.

Subject headings: binaries: close — pulsars: individual (4U 1907+09) — stars: mass loss — stars: neutron — X-rays: stars

1. INTRODUCTION

The X-ray source 4U 1907+09 is a binary system consisting of a neutron star and an early spectral type star. The accretion of matter by the neutron star produces X-ray emission, which has intermittently been studied for nearly three decades since its discovery by Giacconi et al. (1971). Extensive X-ray observations with instruments on board several satellites in the late 1970s and early 1980s have provided the following picture of 4U 1907+09: The neutron star is an X-ray pulsar that in the early 1980s had a pulse period of 437.5 s (Makishima et al. 1984, hereafter M84). The binary orbit has a period of 8.38 days (Marshall & Ricketts 1980, hereafter MR80) and a moderate eccentricity of $0.16^{+0.14}_{-0.11}$ (Cook & Page 1987, hereafter CP87).

The X-ray intensity, on average $\sim$1/100 that of the Crab, varies strongly on many timescales. MR80 noted that 4U 1907+09 almost consistently flares up two times per binary orbit, with the 2–14 keV intensity increasing by about a factor of 5. M84 confirmed the presence of the "primary" and "secondary" flares at the same orbital phases. The secondary flare was seen to vary more than the primary one (MR80). M84 and CP87 suggested that the two flares are due to the orbital plane's being inclined to an equatorial disklike envelope around a Be star: when the neutron star crosses the disk, it temporarily has increased levels of accretion. For 1980 January, 4U 1907+09 was reported to have a monthlong X-ray outburst with a 10 times increase in intensity (MR80).

Van Kerkwijk, van Oijen & van den Heuvel (1989) made a detailed inventory of new, as well as old, optical and X-ray measurements and came to the conclusion that the classification of the optical counterpart (first identified by Schwartz et al. 1980) as an OB supergiant, rather than a Be star, is "virtually certain." For such a classification, the distance would be between 2.4 and 5.9 kpc (van Kerkwijk et al. 1989). With regard to the Be-star explanation for the two flares per orbit, van Kerkwijk et al. evaluated the evidence for a phase-locked secondary flare as not convincing.

Here we report new X-ray observations performed with the proportional counter array (PCA) on board the *Rossi X-Ray Timing Explorer* (*RXTE*). We would like to draw attention to X-ray features never seen before from 4U 1907+09, which may be important in understanding wind accretion in high-mass X-ray binaries—strong intensity dips lasting up to more than an hour. Furthermore, the evolution of the column density of cold circumstellar matter and its implications for the binary environment are briefly discussed. We concentrate on the variability on timescales longer than the pulse period. In a separate paper (in 't Zand, Baykal, & Strohmayer 1997), shorter timescale variability will be dealt with.

2. OBSERVATIONS

The *RXTE* PCA is an array of five identical proportional counters with a total geometric area of $\sim$6250 cm^2 (Zhang et al. 1993). Its large area, combined with its small field of view (FOV), 1° FWHM, enables sensitive, high time resolution observations of X-ray sources in the photon energy range 2–60 keV. *RXTE* is in a low Earth orbit, and thus many observations are interrupted once per orbit by Earth occultations.

We observed 4U 1907+09 with *RXTE* on four occasions, with a total exposure time of 79 ks spanning 5.7 days ($\sim$70% of the binary orbit; the net orbital coverage is 10%). This includes times near to those when the neutron star is closest and farthest from the Sun. Apart from 4U 1907+09, contributions from three other X-ray sources in the FOV are expected: the cosmic diffuse background, the Galactic ridge, and the supernova remnant W49B, which is at a 52′ off-axis location. Since the Galactic ridge emission in the FOV has not yet been accurately measured, its contribution is uncertain. From previous approximate measurements of W49B (Smith et

[1] NAS/NRC research associate; present address: Space Research Organization Netherlands, Sorbonnelaan 2, NL-3584 CA Utrecht, the Netherlands; jeanz@sron.ruu.nl.
[2] Universities Space Research Association research scientist; stroh@lheamail.gsfc.nasa.gov.
[3] NAS/NRC research associate; present address: Physics Department, Middle East Technical University, Ankara 06531, Turkey; altan@astroa.physics.metu.edu.tr.

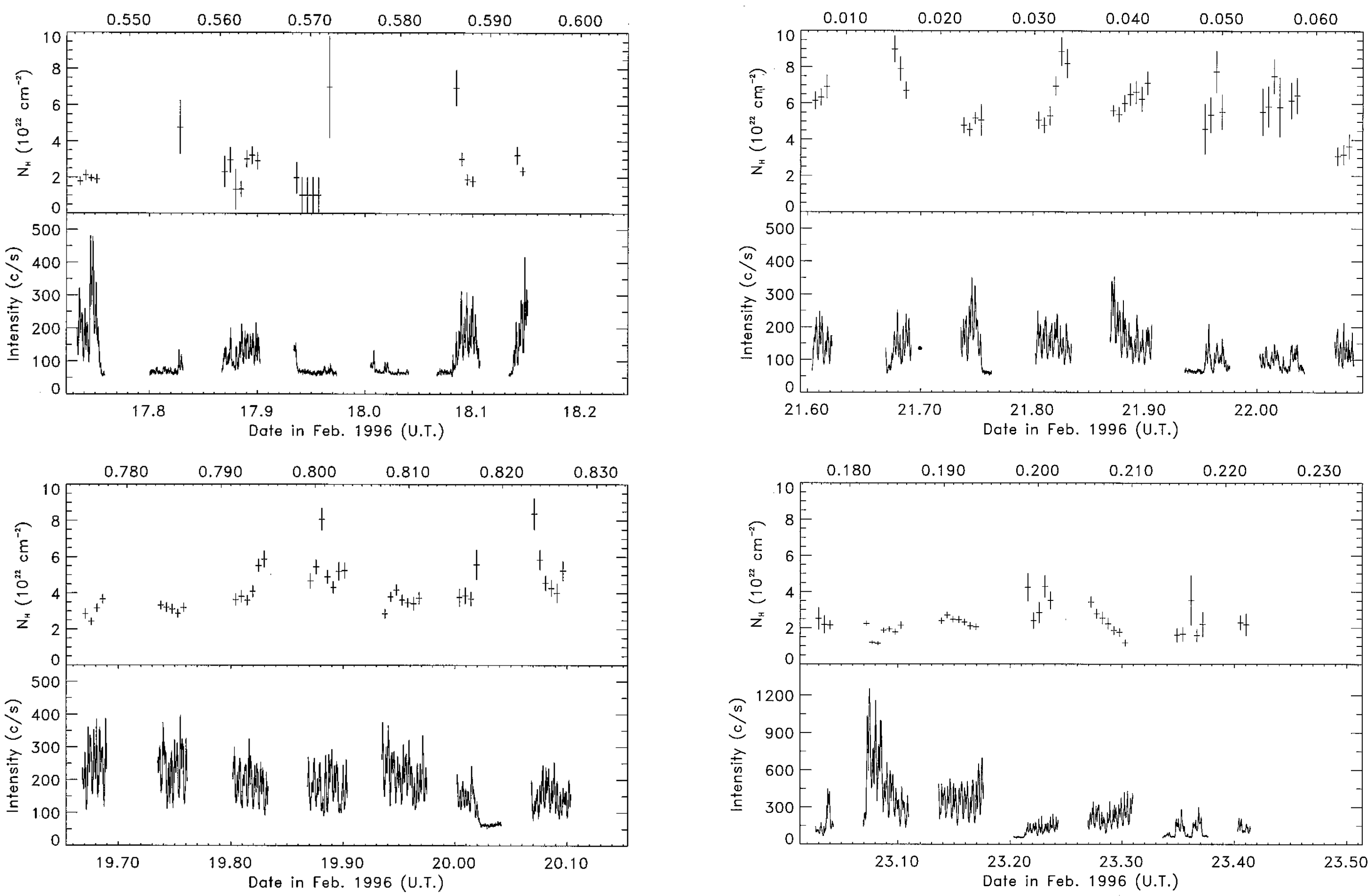

FIG. 1.—Time histories of the raw 2–15 keV intensity (i.e., between pulse-height analyzer [PHA] channels 7 and 55, counting from zero and not correcting for background contributions) and the hydrogen column density of cold circumstellar and interstellar matter (N_H) of the 4U 1907+09 spectrum for the four observational runs. All vertical scales are the same, except for the intensity scale of the fourth run. The time histories of the intensity have a resolution of 8 s, those for N_H a resolution of 440 s (close to the pulse period).

al. 1985) and the Galactic ridge (Koyama 1989; Yamauchi & Koyama 1993), the total background contribution from the three sources is estimated to be 27 counts s^{-1} (2–15 keV) with a systematic uncertainty of 3 counts s^{-1}.

The data collection mode for the four observational runs was event-mode data with 64 energy channels covering the full bandpass and with a time resolution of 16 μs. At the time of the observations, the on-board gain correction algorithm was temporarily turned off (Jahoda et al. 1996). The gains of the five PCA detectors are slightly different. Whenever we quote a photon energy, we refer to that consistent with the channel setting of detector "PCU0." These gain offsets are taken into account during spectral analyses.

We have performed a pulse arrival time analysis (in 't Zand et al. 1997). The resulting orbital phases of the observations are given in Figure 1; the phase is defined with respect to the epoch of maximum distance between the Sun and the neutron star.

3. ANALYSIS

3.1. *X-Ray Light Curve*

The time history of the raw *RXTE* PCA count rate between 2 and 15 keV shown in Figure 1 immediately exhibits one striking behavior: the obvious X-ray pulsar signal dips a number of times to insignificant values. The residual 2–15 keV intensity (corrected for the particle-induced background using the method outlined in § 3.2) during the deepest dips is consistent with the anticipated X-ray background of 27 counts s^{-1}. A number of dips (e.g., those starting on February 17.80 and 17.94 UT) have a clear, weak signal whose variability has timescales similar to that of the signal outside the dips. The intensity of the deepest dips represents a decrease by at least 98% with respect to the average nondip, background-subtracted value of 167 counts s^{-1} given the systematic uncertainty of the background of 3 counts s^{-1}. As long as the contribution from the Galactic ridge is not known more accurately, the upper limit on any residual emission cannot be constrained any further.

In total, at least 11 dips longer than the pulse period were observed over 79 ks of exposure. The duration ranges up to perhaps 1.5 hours. It is not possible to make a definite measurement of the longest duration, because of the gaps in the observations. 4U 1907+09 was seen in a dip phase for 20% of the exposure time. Most dipping activity was seen in the first observational run: the dip phase lasted more than 50% of the time, compared with ~10% for the other three runs. It is difficult to perform a timing analysis on the dipping activity because the typical timescales are similar to that of the

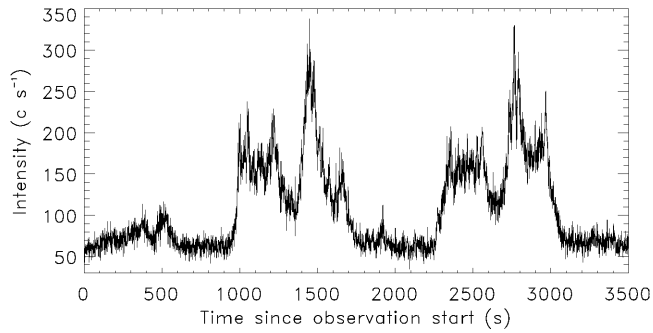

FIG. 2.—Detailed time history of the 2–15 keV intensity for the observation starting on February 23.33 UT; the time resolution is 1 s.

modulation by Earth occultations and other observational constraints. There is no obvious periodicity in the occurrence times. In general, the dips seem to get shorter with time.

In the time history of most dips, the source enters or exits the dips gradually in a few hundred seconds, and the dips seem to last longer than at least 10^3 s. However, in Figure 2 we show a series of unusual dips. The observation starts while 4U 1907+09 is in an incomplete dip, the source then appears relatively fast within ~50 s, stays "on" for almost two pulse periods, and then goes into an incomplete dip for one pulse period. Subsequently, this pattern repeats itself almost exactly, including a resemblance between the first flat-shaped pulses after the dips.

The time history shows a flare at February 23.07 UT, when the net 2–15 keV intensity rises up to $\sim 1.2 \times 10^3$ counts s^{-1} (i.e., the net value is equivalent to 0.1 crab). Given the ephemeris by MR80, the time of the secondary flare detected by M84, and the improved value for the orbital period (in 't Zand et al. 1997), this feature is identified as (possibly part of) the secondary flare first recognized by MR80. The intensity of the flare in the 2–30 keV range is about twice as high as the one measured with *Tenma* (M84). This is not so surprising, since the secondary flare has been seen to vary from insignificant to as bright as the primary flare (MR80).

3.2. *X-Ray Spectrum*

The background consists of the particle-induced background and the X-ray background. The X-ray background spectrum was determined by combining all complete-dip data (i.e., the data without any trace of pulsations) and subtracting the particle-induced background spectrum. The residual spectrum is due to Galactic ridge emission, the cosmic diffuse X-ray background, and W49B emission, as well as possibly some nonpulsed emission from 4U 1907+09. We assume that this residual spectrum is constant throughout our observations; it was so during the complete dips.

Since there is occasionally a lack of information on rates that normally enable one to predict the background spectrum independently (this is not a problem during the complete dips), we employed an alternative method to find the intensity of the particle-induced background spectrum and subtract this spectrum from any arbitrary data: the above X-ray background spectrum was subtracted from each raw spectrum, the result was matched with the constant predetermined spectrum for the particle-induced background beyond approximately 40 keV (PHA channel 132) in order to find its normalization, and the normalized particle-induced background spectrum was subtracted. This method is acceptable because we do not find any evidence for pulsed emission at such high photon energies and because the channel-to-channel variation beyond PHA channel 132 is consistent with what can be expected for the statistical noise around the particle-induced background. A possible complication in this analysis is activation of detector materials by particles, but this effect was found to be negligible in our observations.

A number of candidate spectral models were tested against the average spectrum over all nondip observations in the 2–30 keV range. The best result was obtained for a model found also for other wind-fed X-ray pulsars (see, e.g., White, Nagase, & Parmar 1995): a power-law spectrum with a high-energy cutoff and absorption by cold gas, following the model by Morrison & McCammon (1983). Since the calibration of the PCA is still being refined (Jahoda et al. 1996), we added a 1% systematic error in quadrature to the statistical errors for each channel. The reduced χ^2 is 1.1 for 34 degrees of freedom.

Spectra were generated for the pulsed emission, with a time resolution equal to the pulse period so that spectral changes during pulses are averaged out, and fitted with the aforementioned spectral model. The results for the time history of N_H are displayed in Figure 1. This parameter is particularly interesting to study because it can provide clues toward the cause of the dips and the nature of the binary environment in general. N_H varies between about 1×10^{22} and 9×10^{22} cm^{-2}. On short timescales it may rise by about $(4–5) \times 10^{22}$ cm^{-2}; sometimes but not always this is immediately before or after a long dip. The statistical quality of the data does not permit an accurate study of this in higher time resolution, not even using plain hardness ratios, because of the combination of low intensity levels and fast dip ingress and egress times. On long timescales there is a clear trend in the N_H data: The base level rises gradually from 2×10^{22} cm^{-2} in the beginning to 6×10^{22} cm^{-2} at February 22.0 UT. Then, within ~30 minutes, it drops to 3×10^{22} cm^{-2} and subsequently to values as low as 1.1×10^{22} cm^{-2} during the secondary flare. Because of the correspondence with relatively high X-ray fluxes, the lowest N_H values might be associated with either photoionization or a soft excess.

The other spectral parameters are all relatively constant. The power-law photon index varies between -1.0 and -1.3, which is similar to what was observed by CP87 in *EXOSAT* data, which covered energies up to 15 keV, and the cutoff energy is consistent with a constant value of 13.6 keV. No evidence was found for spectral lines; the 99% confidence upper limit of the intensity of a constant narrow emission line at 6.7 keV is 2×10^{-4} photons s^{-1} cm^{-2} (equivalent width 0.06 keV). The maximum observed absorption can be responsible for a reduction of only 20% in the flux above 1 keV.

We separately analyzed the spectrum at very low but detectable intensity levels of 4U 1907+09 during the dips starting at February 17.80 and 17.94 UT. The combined background-subtracted spectrum for these dips can be satisfactorily modeled by a power-law spectrum with a slightly hard photon index of -0.8 ± 0.1 and a 99% confidence upper limit for N_H of 6×10^{22} cm^{-2}. This suggests that there is no strongly increased absorption at very low intensities. We believe that there is reasonable evidence that the weak emission has the same origin as the strong pulsed emission outside the dips, because the timescales of the variability are similar and the spectral shape is consistent.

4. DISCUSSION

Dipping activity has so far not been recognized in 4U 1907+09. The most sensitive observations at similar photon energies prior to our *RXTE* observations were performed with *Tenma* in 1983 (M84) and *EXOSAT* in 1984 (CP87), both at sensitivities ~3 times worse than the PCA observations. We have found no published timing studies of *Ginga* data. The *Tenma* and *EXOSAT* coverage of the orbit was similar to ours, and the *EXOSAT* observations were not contaminated by constraints typical of low Earth orbit observations. The published reports about these data do not mention complete disappearances of 4U 1907+09 as seen in the PCA data, although we believe that the quality of the data would have permitted seeing dipping activity with such high duty cycles. If indeed the dipping activity is a transient feature, this is not very surprising, as 4U 1907+09 is known to show long-term variability: MR80 saw several kinds of variability over the course of 5 years, including a monthlong outburst in 1980 January.

Dipping activity has been observed in slightly more than 10 X-ray sources, mostly in low-mass X-ray binaries, where it is associated with occultation of the compact X-ray–emitting region near the neutron star by vertical irregularities in an accretion disk. Sometimes a high-mass X-ray binary (HMXB) is thought to be dipping because of cessation of accretion, such as 4U 1700−37 (Haberl, White, & Kallman 1989). This is likely because the mass flow in HMXBs often is through a potentially inhomogeneous wind instead of an accretion disk. Cessation of accretion also appears to be the more likely cause for the dips in 4U 1907+09, rather than occultation, for the following reasons: First, the strong intensity variability outside the dips is accompanied by only modest changes in the spectrum. Second, sometimes weak emission is seen during dips with a lack of strong absorption. Its origin is likely similar to that of the pulsations outside the dips. Thus the immediate neighborhood of the neutron star appears not to be obscured. Third, although there are some correspondences between dips and increases in $N_{\rm H}$ suggestive of occultation, not all dips adhere to that.

We estimate the average nondip and nonabsorbed luminosity above 1 keV to be $8 \times 10^{34} D_{\rm kpc}^2$ ergs s^{-1}, where $D_{\rm kpc}$ is the distance to 4U 1907+09 in kiloparsecs. With the rough distance estimates (see § 1), the luminosity is on average $\sim 10^{36}$ ergs s^{-1}, which tends to be in line with other wind-fed HMXBs with an OB star companion (White et al. 1995). The flux compares to the 1983 *Tenma* data and 1984 *EXOSAT* data within a factor of 2.

The cause of the suspected drops in accretion rate is not clear. They are almost certainly not caused by centrifugal inhibition of accretion (Stella, White, & Rosner 1986), as the corotation radius (10^5 km) is much larger than any imaginable value of the Alfvén radius of the neutron star magnetosphere (10^3–10^4 km for a dipole moment of 10^{30} G cm^3 and a mass accretion rate equivalent to the above average luminosity). Sometimes the data (see Fig. 2) do suggest that the rotating magnetosphere is important in modulating the accretion rate. Otherwise, inhomogeneities in the mass stream from the companion star are most likely responsible for the deep drops in the accretion rate. Rather than blobs (see, e.g., White, Kallman, & Swank 1983), the inhomogeneities may consist of holes of reduced mass flux. Photoionization is a candidate process that could induce such holes, through the indirect suppression of the radiative force that drives stellar winds (MacGregor & Vitello 1982). If this is the case, one would expect a degree of correlation between X-ray flares and dips with delay times on the order of a few hours or more for a wind speed of 1000 km s^{-1} or less. Our data set does not allow a conclusive check on this.

We see a short flare at an orbital phase consistent with that of the secondary flare recognized by MR80 and M84, so it appears that the secondary flare is indeed phase-locked. We are not in a position to confirm the presence of the primary flare. Both the secondary flare's occurrence and the evolution of $N_{\rm H}$, whose base level shows an increase up to February 22.05 UT, seem to confirm earlier suggestions by M84 and CP87 of an equatorial disk around the companion star. However, alternative explanations seem possible, such as a gas stream trailing the neutron star in its orbit (the evolution of the $N_{\rm H}$ base level looks similar to that in Vela X-1; see Haberl & White 1990), which may be crossed by the neutron star as a result of the orbit's eccentricity (as suggested for GX 301−2; see Haberl 1991). Observations with a higher net orbital coverage may enable a more useful comparison between models.

We thank the members of the *RXTE* Guest Observer Facility for their help in the data reduction. J. Z. and A. B. acknowledge the support under the research associateship program of the US National Research Council. T. S. acknowledges the support of the HEAP program of the Universities Space Research Association at NASA's Goddard Space Flight Center.

REFERENCES

Cook, M. C., & Page, C. G. 1987, MNRAS, 225, 381 (CP87)
Giacconi, R., Kellogg, E., Gorenstein, P., Gursky, H., & Tananbaum, H. 1971, ApJ, 165, L27
Haberl, F. 1991, ApJ, 376, 245
Haberl, F., & White, N. E. 1990, ApJ, 361, 225
Haberl, F., White, N. E., & Kallman, T. R. 1989, ApJ, 409, 425
in 't Zand, J. J. M., Baykal, A., & Strohmayer, T. E. 1997, in preparation
Jahoda, K., Swank, J. J., Giles, A. B., Stark, M. J., Strohmayer, T., & Zhang, W. 1996, Proc. SPIE, 2808, 59
Koyama, K. 1989, PASJ, 41, 665
MacGregor, K. A. B., & Vitello, P. A. J. 1982, ApJ, 259, 267
Makishima, K., Kawai, N., Koyama, K., Shibazaki, N., Nagase, F., & Nakagawa, M. 1984, PASJ, 36, 679 (M84)
Marshall, N., & Ricketts, M. J. 1980, MNRAS, 193, 7P (MR80)
Morrison, R., & McCammon, D. 1983, ApJ, 270, 119
Schwartz, D. A., Griffiths, R. E., Thorstensen, J. R., Charles, P. A., & Bowyer, S. 1980, AJ, 85, 549
Smith, A., Jones, L. R., Peacock, A., & Pye, J. P. 1985, ApJ, 296, 469
Stella, L., White, N. E., & Rosner, R. 1986, ApJ, 308, 669
van Kerkwijk, M. H., van Oijen, J. G. J., & van den Heuvel, E. P. J. 1989, A&A, 209, 173
White, N. E., Kallman, T. R., & Swank, J. H. 1983, ApJ, 269, 264
White, N. E., Nagase, F., & Parmar, A. N. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ Press), 1
Yamauchi, S., & Koyama, K. 1993, PASJ, 404, 620
Zhang, W., Giles, A. B., Jahoda, K., Soong, Y. Swank, J. H., & Morgan, E. H. 1993, Proc. SPIE, 2006, 324