The Astrophysical Journal, 703:325–329, 2009 September 20 doi:10.1088/0004-637X/703/1/325

A MEASUREMENT OF THE ADIABATIC COOLING INDEX FOR INTERSTELLAR HELIUM PICKUP IONS IN THE INNER HELIOSPHERE

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Received 2009 March 31; accepted 2009 July 22; published 2009 August 27

ABSTRACT

Interstellar neutral gas enters the inner heliosphere where it is ionized and becomes the pickup ion population of the solar wind. It is often assumed that this population will subsequently cool adiabatically, like an expanding ideal gas due, to the divergent flow of the solar wind. Here, we report the first independent measure of the effective adiabatic cooling index in the inner heliosphere from *SOHO* CELIAS measurements of singly charged helium taken during times of perpendicular interplanetary magnetic field. We use a simple adiabatic transport model of interstellar pickup helium ions, valid for the upwind region of the inner heliosphere. The time averaged velocity spectrum of helium pickup ions measured by CELIAS/CTOF is fit to this model with a single free parameter which indicates an effective cooling rate with a power-law index of $\gamma = 1.35 \pm 0.2$. While this average is consistent with the "ideal-gas" assumption of $\gamma = 1.5$, the analysis indicates that such an assumption will not apply in general, and that due to observational constraints further measurements are necessary to constrain the cooling process. Implications are discussed for understanding the transport processes in the inner heliosphere and improving this measurement technique.

Key words: ISM: kinematics and dynamics – magnetic fields – plasmas – solar–terrestrial relations – solar wind

1. INTRODUCTION

Vasyliunas & Siscoe (1976, henceforth V&S) predicted a population of interstellar pickup ions (PUIs) on the solar wind formed from interstellar neutrals, which penetrate the heliosphere and become ionized by solar radiation. The first such PUI population was observed with the AMPTE spacecraft (Möbius et al. 1985) by identification of singly charged helium with a characteristic cutoff velocity. As pickup ion observational techniques improved, they expanded to include additional species (e.g., Gloeckler et al. 1993) and a number of variations from the simple model of V&S became evident. For example, suprathermal tails on the PUI velocity distribution indicate acceleration processes (e.g., Fisk & Gloeckler 2006), and anisotropies in the velocity distribution indicate that pitch-angle scattering to isotropy is not as fast as originally expected (e.g., Saul et al. 2007). Here, we examine in detail the assumption that pickup ions will cool in the expanding solar wind.

As the solar wind expands outward in the heliosphere, it fills a progressively larger volume. Conservation of phase space thus suggests that internal forces will cool the particles. For a pickup ion injected at a position r at a velocity V_{SW} (in the solar-wind frame), and convected out to a position r_0, we can assume that the cooling leading to a velocity v at r_0 is a power law:

$$v = V_{SW} \left(\frac{r}{r_0} \right)^{\gamma} . \quad (1)$$

For the case of an ideal gas expanded with a piston, one can calculate the cooling rate from the microphysics of the system, namely collisions of the particles with the moving piston. Assuming the same adiabatic behavior, now as caused by interactions of the particles with fluctuations in the interplanetary magnetic field (IMF), recovers the assumption of V&S, namely that in Equation (1), $\gamma = 3/2$.

However, for the case of the collisionless plasma of the solar wind, the microphysics is controlled not by Coulomb collisions but by confining magnetic field lines. For example, if the magnitude of the magnetic field was inversely proportional to the square distance from the Sun, conservation of the 1st magnetic adiabatic moment alone leads to $\gamma = 1$. Magnetic cooling due to motion parallel to the field (and conservation of the 2nd moment) leads to further cooling (Fahr 2007; Fahr & Siewert 2008). Further, the addition of resonant magnetohydrodynamic waves that pitch-angle scatter the particles (see e.g., Qin et al. 2006) can violate the required conditions for conservation of magnetic adiabatic invariant, and the pickup ions are cooled still more. For the case of the solar wind itself as it moves into the outer heliosphere, the temperature is known to not cool as an ideal gas, due to the additional energy provided by the injection of PUIs (Isenberg et al. 2003; Smith et al. 2001; Fahr & Chashei 2002; Chashei et al. 2003). For these reasons, we suggest that the original assumption of V&S with regard to the cooling rate is worth additional scrutiny (see also Marsch 1991). However, in this paper we treat γ as an independent parameter and we allow it to vary in a simple model, to match observations. We also note that this is an average γ over the entire transport of the ions from pickup to observation, and so does not reflect likely variations in cooling rates with heliocentric distance, as the field geometry changes.

2. SIMPLIFIED PUI TRANSPORT MODEL

2.1. Interstellar Neutral Density

The starting point for a model of PUIs is the density of neutral atoms in the heliosphere. To calculate this neutral density, we consider a cold model of interstellar neutrals on the upwind side of the heliosphere, which is justified by the upwind locations of CTOF/CELIAS during the periods of observation and the small difference between cold and hot models here. This allows us to solve for a steady-state density of neutral helium as a function of heliocentric distance

$$N_0[r] = A \exp \left[-\frac{\beta_0 r_0^2}{G M_\odot} \sqrt{v_\infty^2 + 2GM_\odot / r} \right] . \quad (2)$$

Here, we have used the fact that radiation pressure does not influence the trajectory of the incoming noble gas atoms, and we take the ionization rate to be a constant at $r_0 = 1$ AU, as $\beta_0 = 6.0 \times 10^{-8}$ s^{-1} (Rucinski et al. 1996; McMullin et al. 2002) and the motion of a neutral atom far from the Sun as 26.2 km s^{-1} (Möbius et al. 2005). The normalization factor A is chosen so that the interstellar density is recovered for large r.

2.2. Integration of Injected Ring Distribution—Isotropic Model

As a packet of solar-wind ions moves outward, helium pickup ions collect due to photoionization. We can build up the pickup ion distribution by following the packet of ions outward from the Sun. As the packet passes from a heliocentric distance r to $r + dr$, it collects an increment in number density of injected pickup ions

$$dn = \frac{\beta_0 r_0^2}{r^2} N_0(r) \frac{dr}{V_{SW}}, \tag{3}$$

where $N_0(r)$ is the neutral density at the distance r, and β_0 is the ionization rate at $r_0 = 1$ AU. The ionization of these neutrals occurs during a time dr/V_{SW}. Newly ionized pickup ions immediately begin gyration about the magnetic field, and the injected velocity distribution forms a ring in velocity space. Because the pickup ions are injected at a single velocity (cold model of interstellar neutrals), the increment to the distribution function will take the form of a delta function

$$dF(v, r) = dF(r)\delta(v - v_0(r)). \tag{4}$$

Here, $dF(v, r)$ is the increment to the total pickup ion distribution function accumulated over heliocentric distance from r to $r+dr$. The velocity v_0 at which the ring appears in the final distribution depends on r due to the cooling, i.e., $v_0(r) = V_{SW}(r/r_0)^\gamma$.

When integrated over all velocity space, this increment of distribution function will yield the increment of injected density at a heliospheric distance r,

$$dn = dF(r) 4\pi v_0^2. \tag{5}$$

Equating this with Equation (3) allows us to calculate the radial dependence

$$dF(r, v) = \frac{\beta_0 r_0^2 N_0(r)\delta(v - v_0)dr}{4\pi v_0^2 V_{SW} r^2}. \tag{6}$$

We can now integrate over the travel of the solar-wind packet from 0 to 1 AU, collecting the entire pickup distribution along the way. The total pickup ion velocity distribution $f(v)$ at 1 AU is

$$f(v) = \int_0^{1\,\mathrm{AU}} dF_{inj}(r, v) = \frac{\beta_0 r_0^2}{4\pi V_{SW}} \int_0^{r_0} \frac{N_0(r)\delta(v - v_0)}{r^2 v_0^2} dr. \tag{7}$$

Evaluation of the integral over the delta function proceeds via the identity

$$\int_0^{r_0} h(r)\delta(g(r))dr = \sum_i \frac{h(r_i)}{|g'(r_i)|}, \tag{8}$$

where r_i are the roots of $g(r)$, such that $g(r_i) = 0$. Let $g(r) = v - v_0$. Evaluation of the integral in Equation (7) then gives

$$f(v) = \frac{\beta_0 r_0^2}{4\pi V_{SW}} \frac{N_0(r_i)}{r_i^2 v_0(r_i)^2} \frac{1}{|g'(r_i)|}, \tag{9}$$

where $g(r) = v - v_0$, therefore using the power-law assumption for adiabatic cooling in Equation (1),

$$g'(r) = -\frac{\gamma V_{SW}}{r_0} \left(\frac{r}{r_0}\right)^{\gamma - 1},$$

we also can solve for the single root of $g(r)$,

$$r_i = r_0 \left(\frac{v}{V_{SW}}\right)^{1/\gamma} \qquad v_0(r_i) = v.$$

The integration over the travel of the solar-wind packet in Equation (7) can now be calculated, and the observed distribution will be

$$f(v) = \frac{\beta_0 r_0}{4\pi\gamma V_{SW}^4} \frac{N_0(r_0 w^{1/\gamma})}{w^{3+1/\gamma}}, \tag{10}$$

where we have substituted $w = v/V_{SW}$. At this point, we can note that the flux J of PUIs observed to be moving at speed v will be

$$J(v) = \frac{v^2}{m} f(v) = \frac{V_{SW}^2}{m} w^2 f(v), \tag{11}$$

and the differential energy flux,

$$JE(v) = \frac{\beta_0 r_0}{4\pi\gamma} N_0(r_0 w^{1/\gamma}) w^{1-1/\gamma}. \tag{12}$$

It is important to note that this differential energy flux is independent of solar-wind speed (see, e.g., Möbius et al. 1995), and so we use this quantity when combining pickup ion spectra from time periods with different solar-wind speeds.

2.3. Aperture Integration

During times of radial IMF, pickup ions are injected in the sunward hemisphere of velocity space, i.e., moving toward the Sun. They must then be pitch angle scattered to the anti-sunward hemisphere if they are to be accessible to the charge time-of-flight (CTOF) aperture and energy acceptance range. For this reason, there has been observed a smaller pickup ion flux during times of radial IMF (Möbius et al. 1998) and the flux spectra become indicative of the pitch angle scattering rate (Saul et al. 2007). For the case of perpendicular IMF, injected pickup ions immediately gyrate around the magnetic field and do not need scattering to be accessible to the instrument. For studying the adiabatic cooling rate, this is an improvement because the velocity spectrum is to first order no longer dependent on the pitch angle scattering rate. For this reason, explicit dependence on pitch angle was left out of the simple model leading to Equation (12).

To take advantage of this effect, we accumulate PUI spectra during times when the IMF is from 85° to 90° from the Earth–Sun line. During these times, we expect the energy flux spectrum given in Equation (12) to have a velocity dependence given by

$$JE(v) \sim N_0[r_0 w^{1/\gamma}] w^{1-1/\gamma}. \tag{13}$$

3. INSTRUMENTATION

The CELIAS instrument package on board *Solar and Heliospheric Observatory* (*SOHO*) contained a CTOF spectrometer, which sampled solar wind for six months in 1996. Because of the large geometric factor of this instrument and the constant sampling of the solar wind (*SOHO* lives at the L1 point), this

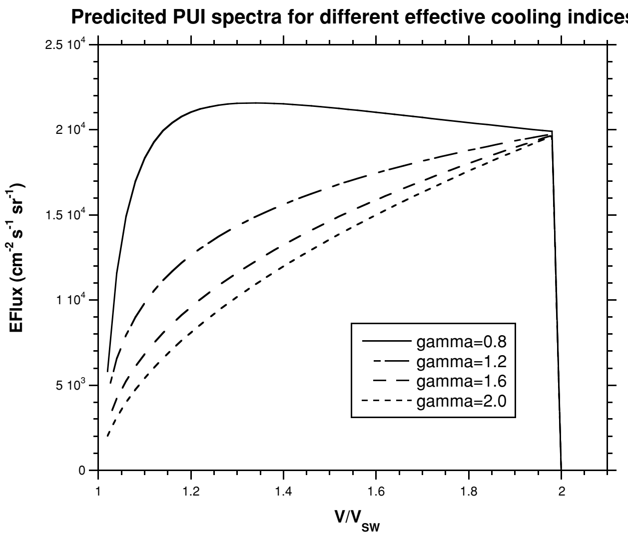

Figure 1. Predictions of pickup ion velocity spectra in spacecraft reference frame are shown for four different values of effective adiabatic cooling index *gamma*. The spectra are shown in velocity normalized to the solar-wind speed.

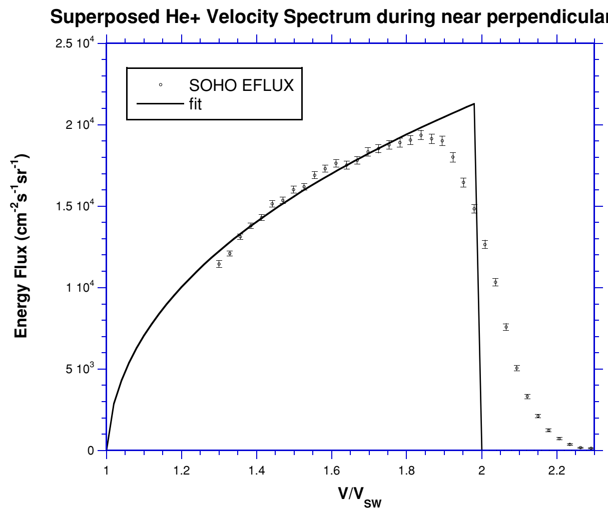

Figure 2. Best-fit model is shown with the averaged *SOHO* measurement of interstellar pickup He. The normalized velocity is given in the spacecraft frame. The error bars show the statistical error due to the number of counts in a given energy bin.

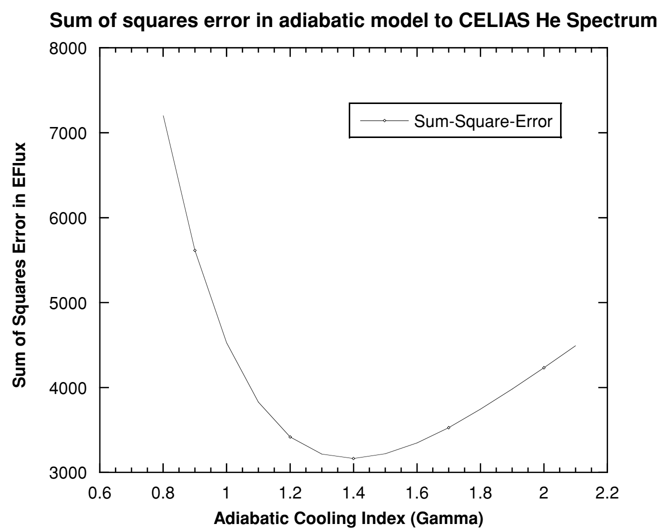

Figure 3. For different values of the adiabatic index gamma, the error of the associated model is computed as the sum of squares of the difference from each CELIAS observed point to the model prediction. The predicted best fit for an ideal gas or the V&S model at 3/2 is shown with a vertical line.

data set is our highest time resolution sample of the interstellar helium PUI population (Aellig & Bochsler 1998; Hovestadt et al. 1995). Although the *SOHO* spacecraft was not equipped with a magnetometer, we can infer the field at *SOHO* by using the magnetometer data from *WIND* (as used in Möbius et al. 1998; Saul et al. 2004a; see also Matsui et al. 2002).

4. BEST-FIT COOLING PARAMETER

Using Equation (12), we can see how the time-averaged pickup ion velocity distribution will vary with the effective adiabatic cooling parameter. We take $N_{HE} = 0.015\ \mathrm{cm}^{-3}$ for the local interstellar helium density (Möbius et al. 2005), and $\beta_0 = 6 \times 10^{-8}$ as the ionization rate of helium at 1 AU (McMullin et al. 2002) during the observations. The form of the distribution is shown in Figure 1 for four values of the index *gamma*.

By using a least-squares fitting procedure, we can determine the best value of the cooling parameter that matches the observed PUI spectrum. To eliminate effects associated with acceleration and with a cutoff shift due to nonzero injection speed (Möbius et al. 1999), we only fit the model to that portion of the spectrum where $V/V_{\mathrm{SW}} < 1.85$. Computationally this is a two parameter fit procedure, with gamma as the first parameter and the normalization as the second, which we carried out using the Simplex algorithm to minimize squared error. Effectively, the shape of the spectra is fixed with a one parameter fit.

It can be seen in Figure 2, which compares the observations to the model, that there are some features that do not match the model. The presence of some pickup ions after the cutoff velocity can be explained by acceleration mechanisms which act on the pickup ion distribution even in quiet solar wind. Another feature in which the observations diverge from the simple model presented here is the onset of lower flux before the cutoff velocity is reached. This is likely due to the fact that the sampled intervals include some time periods when the magnetic field was not exactly perpendicular, and when pitch-angle scattering is thus required to bring the pickup ions into the observable range of the instrument. This feature will be enhanced not only by the chosen set of time periods being not precisely perpendicular (85° to 90° was used) but also by any systematic errors in determining the magnetic field direction at *SOHO* from the measurement at *WIND*.

Figure 3 shows the goodness of fit with the model over a range of adiabatic cooling index γ. Although the best-fit parameter of 1.35 is slightly less than the ideal value of $\gamma = 1.5$, it can be seen that the difference in model accuracy at predicting the observations is small. The slower cooling predicted pure magnetic cooling (e.g., conservation of magnetic moment in a purely radial field, $\gamma = 1$), is excluded by this result.

The form of the velocity distribution in the Equation (12) that we use to find the best-fit cooling index also depends on the ionization rate, through the neutral density (Equation (2)). Although the ionization rate was more stable at solar minimum when these observations were made, there is still some variation and uncertainty which affects the best-fit cooling parameter. Figure 4 shows how the assumption of ionization rate affects the best-fit adiabatic cooling parameter for a large range of ionization rates. Considering this range of ionization rates leads to a range of

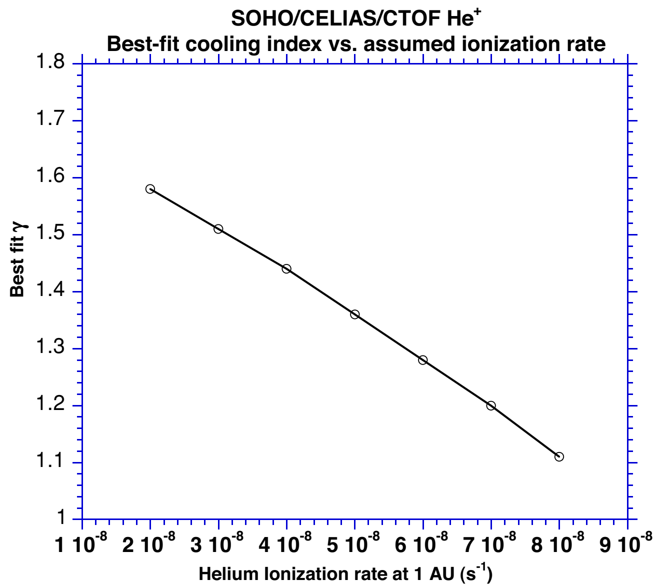

Figure 4. Best-fit adiabatic cooling index for interstellar pickup He is shown as a function of assumed ionization rate at 1AU β_0. The value for $\beta_0 = 6 \times 10^{-8}$ is the one reported here (see McMullin et al. 2002).

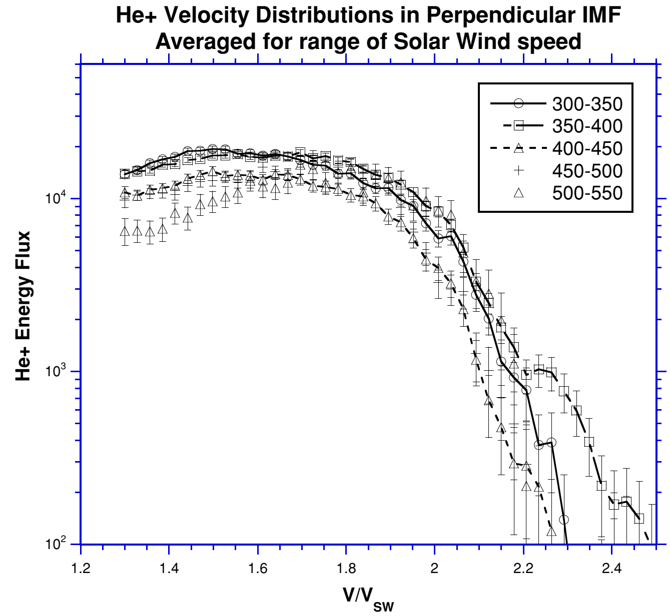

Figure 5. Singly charged helium energy flux spectra are shown divided into five ranges of co-measured solar-wind speed, only taken during times of near perpendicular IMF. Error bars repress statistical error from the number of counts.

values of the adiabatic cooling index consistent with the observations: $\gamma = 1.35 \pm 0.2$. We have assumed here a constant ionization rate to arrive at the neutral density given by Equation (2). A numeric time-dependent model would be required to improve on this assumption, beyond the scope of this report (see Bzowski 2001). This cooling index represents an average cooling over all of the transport. In reality, the instantaneous cooling rate or even the average cooling rate at a given heliocentric distance could be different, due to the different magnetic field geometry at different heliocentric distances (the Archimedean spiral). Further, this model does not include the affects of energy diffusion due to wave/particle interactions (see Chalov & Fahr 1998; Saul et al. 2004b)

A further consideration of sources of error for this calculation arises indirectly from looking at the PUI velocity spectrum as a function of solar-wind speed. If the assumptions leading to Equation (12) are correct, there should be no dependence of the energy flux density on solar-wind speed. However, some dependence is observed in the data, when the events are separated based on co-measured solar-wind speed from MTOF-PM aboard *SOHO* (see Figure 5). An analysis of these curves based on previous assumptions would suggest that the PUIs are cooled more quickly in fast wind than slow wind. Unfortunately, the statistics of the CTOF data set do not include enough accumulation time for each range of solar-wind speeds to trust these curves, due to the variability of PUI spectra over small timescales. Normally, large time averages are employed to avoid such fluctuations (e.g., Gloeckler & Geiss 2006; Möbius et al. 2005). We also considered the hypothesis that an systematic energy dependence of the CTOF calibration could cause such a dependence on solar-wind speed. A numeric model of the entrance system (Aellig & Bochsler 1998) showed only a small additional effect for this energy range. Another potential source of the variation with solar-wind speed is due to a correlation with ionization rate. Coronal holes which produce fast wind also produce a different UV flux, which could affect the ionization rate. However, any systematic error in the energy dependent efficiency of CELIAS/CTOF would affect the spectral slope and hence the fitting parameter gamma. The dependence of our numerical result is here dependent on a difficult calibration, and an in-flight calibration procedure and/or a set of measurements would be required for that result to be conclusive. A meaningful analysis of the cooling rate as a function of solar-wind speed will also have to wait for a set of pickup ion measurements with a longer time integration than six months of data from CELIAS/CTOF.

5. DISCUSSION

It is in some ways remarkable that the pickup ion population, a non-Maxwellian unstable distribution in a collisionless plasma, could cool in a similar manner to the thermodynamics of a dense gas. However, these measurements indicate that pickup ions in the inner heliosphere cool faster than a pure radial magnetic adiabatic model would suggest, very close to the rate of an ideal gas. The difference from the model of V&S and the *SOHO*/CELIAS/CTOF measurements in our comparative region is within uncertainties. However, the difference may be important for understanding the transport physics in the inner heliosphere and for making precise predictions of the effects of pickup ions in the outer heliosphere, such as charge exchange ionization rates. The observed variations in the helium pickup ions point out that in general such a model does not predict the instantaneous energy spectrum well.

The best-fit value of cooling index reported here implies that the pickup ions may cool slightly quicker than expected. This additional loss of energy must go somewhere, and the obvious places are the solar-wind magnetic fields (through generation of waves) and the solar-wind kinetic energy (temperature). The fact that the observed PUI distribution does not agree with the prediction of a conserved adiabatic magnetic invariant $\mu = \frac{v_\perp^2}{B}$ is strong evidence that resonant Alfvénic fluctuations in the solar wind have a crucial effect on particle transport. These fluctuations must act to quickly isotropize the distribution. However, some evidence has shown that pitch-angle scattering is slower than expected (Möbius et al. 1998; Saul et al. 2007). These observations can be explained by e.g., a hemispheric model of pitch-angle scattering (Isenberg 1997). In such a model, the pitch-angle scattering is fast enough to explain the adiabatic cooling but does not quickly scatter particles across the 90° pitch angle.

Future studies of the cooling rate of pickup ions in the inner heliosphere using this technique will be improved by adapting a more sophisticated model such the hemispheric model, but will also be greatly aided by improvement of measurement techniques allowing co-measurement of the IMF, better time coverage, angular range, and better statistics.

This work was also supported by the National Science Foundation under grant 0502324. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Discussions with Peter Bochsler were helpful to motivate this work, which would not be possible without the suggestions and detailed work of Eberhard Möbius. Analysis by Phil Isenberg was also helpful. The Swiss National Foundation is acknowledged.

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