SPATIAL VARIATION OF IRON ABUNDANCE IN THE HIGH SPEED SOLAR WIND, 1972 - 1976

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ABSTRACT

We have analyzed the Fe/H ratios in the peaks of high speed streams (HSS) during the decline of Solar Cycle 20 and the following minimum (October 1972-December 1976). We utilized the response of the 50-200 keV ion channel of the APL/JHU energetic particle experiment (EPE) on IMP-7 and 8 to solar wind iron ions at high solar wind speeds ($V \geq 600$ km sec^{-1}), and compared our Fe measurements with solar wind H and He parameters from the Los Alamos National Laboratory (LANL) instruments on the same spacecraft In general, the Fe distribution parameters (bulk velocity, flow direction, temperature) are found to be similar to the LANL He parameters. Although the average Fe/H ratio in many steady HSS peaks agrees within observational uncertainties with the nominal coronal ratio of 4.7×10^{-5}, abundance variations of a factor of up to 6 are obtained across a given coronal-hole associated HSS. Over the period 1973-1976, a steady decrease in the average quiet-time Fe/H ratio by a factor of about 4 is measured on both IMP-7 and 8. A more detailed discussion of these findings, as well as Fe/H variations correlated with solar flare activity, can be found in Mitchell et al. (1983).

INTRODUCTION

Contemporary plasma detectors (electrostatic analyzers and mass spectrometers) are limited in measuring iron ions at high solar wind speeds (> 600 km sec^{-1}) with their attendant high kinetic temperatures. An alternate, though unexpected, technique has been shown in Mitchell and Roelof (1980) and Mitchell et al. (1981), hereafter referred to as Papers 1 and 2, to be capable of high time resolution measurements of solar wind iron under precisely these conditions. The technique uses the 50 - 200 keV ion channel of the Energetic Particle Experiments (EPE), D. J. Williams, Principal Investigator, on the IMP 7/8 spacecraft. Another measurement of iron in high speed solar wind, including charge state determination, was reported by Ipavich et al. (1983) who also employed a solid state detection system. In addition to being able to measure iron at high bulk velocities, the uniqueness of the observations presented here lies in their continuity over time scales of hours, days, or years so that we can investigate variations in abundance and other distribution function parameters in individual streams, and even the evolution of streams themselves over the decline of the last solar cycle.

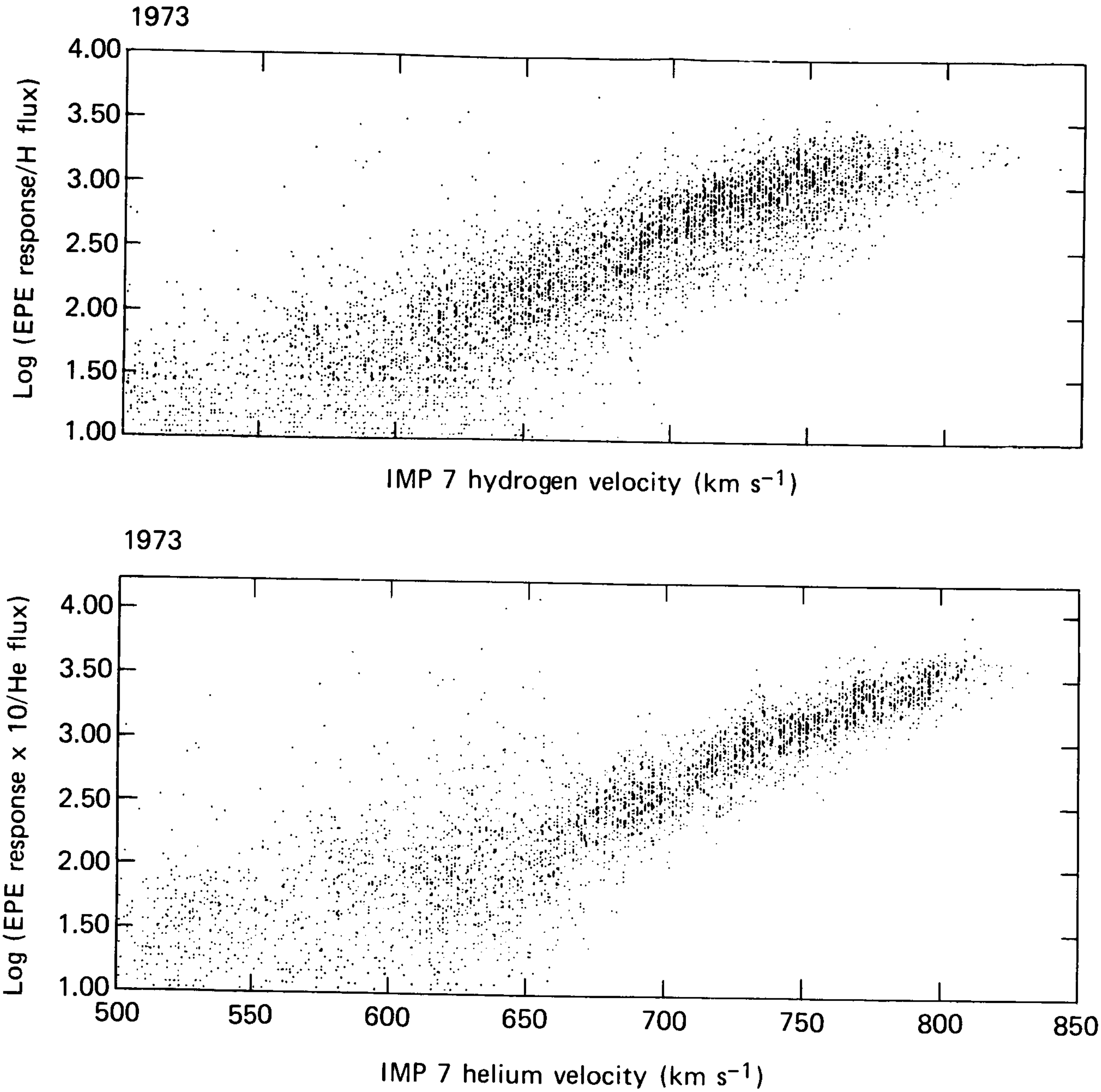

FIGURE 1 (a) Scatter plot of the logarithm of the EPE L1 detector iron response (5.5 minute averages) normalized by the LANL hydrogen flux, versus the LANL hydrogen velocity for all $V_H > 500$ km s^{-1} during 1973. (b) Scatter plot of the logarithm of the EPE L1 detector iron response normalized by the LANL helium flux, versus the LANL helium velocity. Note the reduced scatter above $V_{He} \sim 660$ km s^{-1}.

TECHNIQUE

As described in Papers 1 and 2, the iron is seen primarily in Sectors 9 and 10, the sunward-looking sectors of the 16 sectors in the ecliptic plane. In Paper 2, we describe in detail a method whereby for certain events we can derive both the iron bulk flow velocity (V_{Fe}) and its thermal velocity (v_{Fe}), assuming a convected Maxwellian thermal iron distribution. Using the model from Paper 2 for the instrument response based upon detector calibrations and geometry, we can use the measured V_{Fe} and v_{Fe} to obtain the iron flux, $J_{Fe} = N_{Fe} V_{Fe}$. This work will concern itself primarily with the quantity $J_{Fe}/J_H = N_{Fe} V_{Fe}/N_H V_H \approx N_{Fe}/N_H$, the iron abundance relative to hydrogen in the solar wind. We shall use the notation Fe/H for this abundance ratio through the remainder of this paper.

It has been shown (Ogilvie, 1980; Bochsler and Geiss, 1982) that minor ions up to oxygen, and perhaps iron, behave similarly to each other (same bulk velocity and thermal velocity) but dissimilarly to hydrogen (different, usually higher bulk velocity) in the non-collisional solar wind. In Figure 1a, we plot 5.5 minute averages of the sum of the count-rates in Sectors 9 and 10 on IMP-7 normalized by hydrogen flux, versus the hydrogen bulk velocity from the Los Alamos National Laboratory (LANL) solar wind detector on IMP-7. In Figure 1b we plot the sum of Sectors 9 and 10 normalized by the LANL helium flux, versus the LANL helium velocity. It can readily be seen that V_{He} orders the data much better than V_H, in agreement with $V_{He} \simeq V_{Fe} \neq V_H$. Throughout the remainder of this paper, we assume $V_{Fe} = V_{He}$ and use V_{He} to remove the detector efficiency velocity dependence.

IRON ABUNDANCE AS A FUNCTION OF HELIOGRAPHIC SOURCE LONGITUDE

Since we are interested in the coronal source regions and their influence on Fe/H, we wish to examine the variation of Fe/H as a function of the heliographic location of its source in the corona. To this end we shall map the time-ordered data into bin-averaged 2° wide bins in heliographic source longitude, using the constant radial velocity approximation from the corona to 1 AU.

In Figure 2, we show two consecutive recurrences of a particularly broad stream, with the first occurrence in light lines (V_H) and dots (V_{He}), the second in heavy lines and dots. The second panel displays Fe/H normalized by the coronal value of 4.7×10^{-5} of Withbroe (1971), which is also nearly the same as the solar wind value of 5.3×10^{-5} obtained (at lower solar wind velocity and kinetic temperature than those at which we are working) by Bame et al. (1979) for interstream solar wind. The absolute normalization of Fe/H is not well determined; flight spare detectors were used in the detector calibrations, and though there is good qualitative agreement between IMP-7, IMP-8, and the spare detectors, when simultaneously sampling data from a particular stream IMP-7 and 8 disagree with one another by a factor of ~ 3 in absolute response. On the basis of that consistent pattern, we have removed that factor of 3 difference in this paper, multiplying all IMP-7 data by 3 before plotting.

Although the stream's leading edge has moved westward approximately 40° on the second occurrence, the average value of Fe/H has not changed significantly, and, in fact, can be considered a stable signature of this source region. This stream is unusual in its breadth and the good coverage by IMP-7

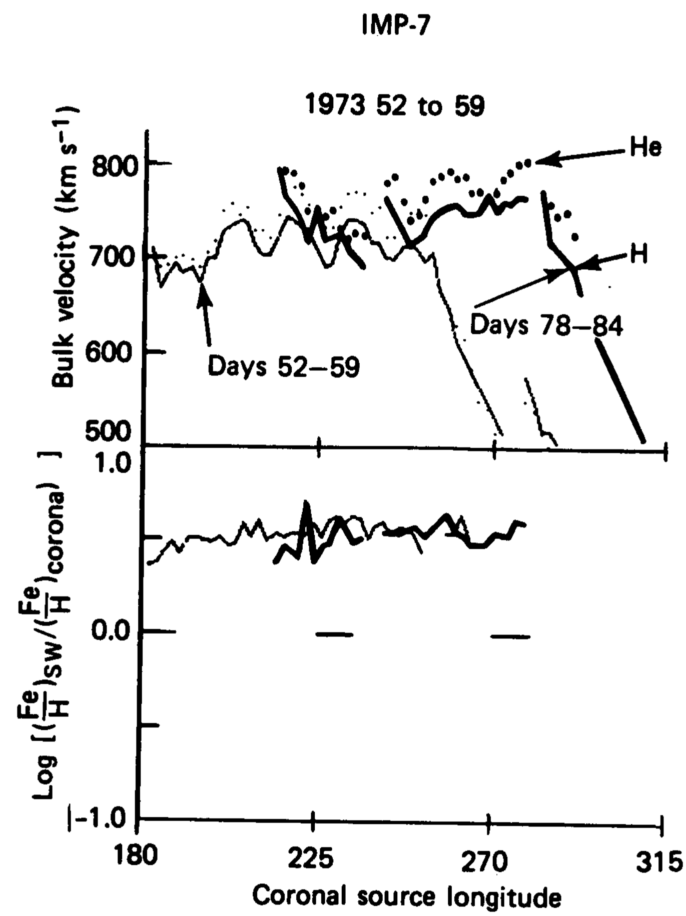

FIGURE 2 IMP-7 LANL solar wind parameters and the EPE iron abundance for a coronal hole-associated high velocity stream, days 50 - 62, 1973, (light lines and dots), plus its recurrence on the following rotation (heavy lines and dots) plotted as a function of heliographic source longitude, assuming constant radial flow from the corona to 1 AU. The top panel shows V_H (solid line) and V_{He} (dots). Second panel is the logarithm of the measured iron abundance (Fe/H) normalized by a coronal value of 4.7×10^{-5}.

on consecutive rotations, but the repeatability of the Fe/H profile is a common feature of other stable corotating streams associated with coronal holes.

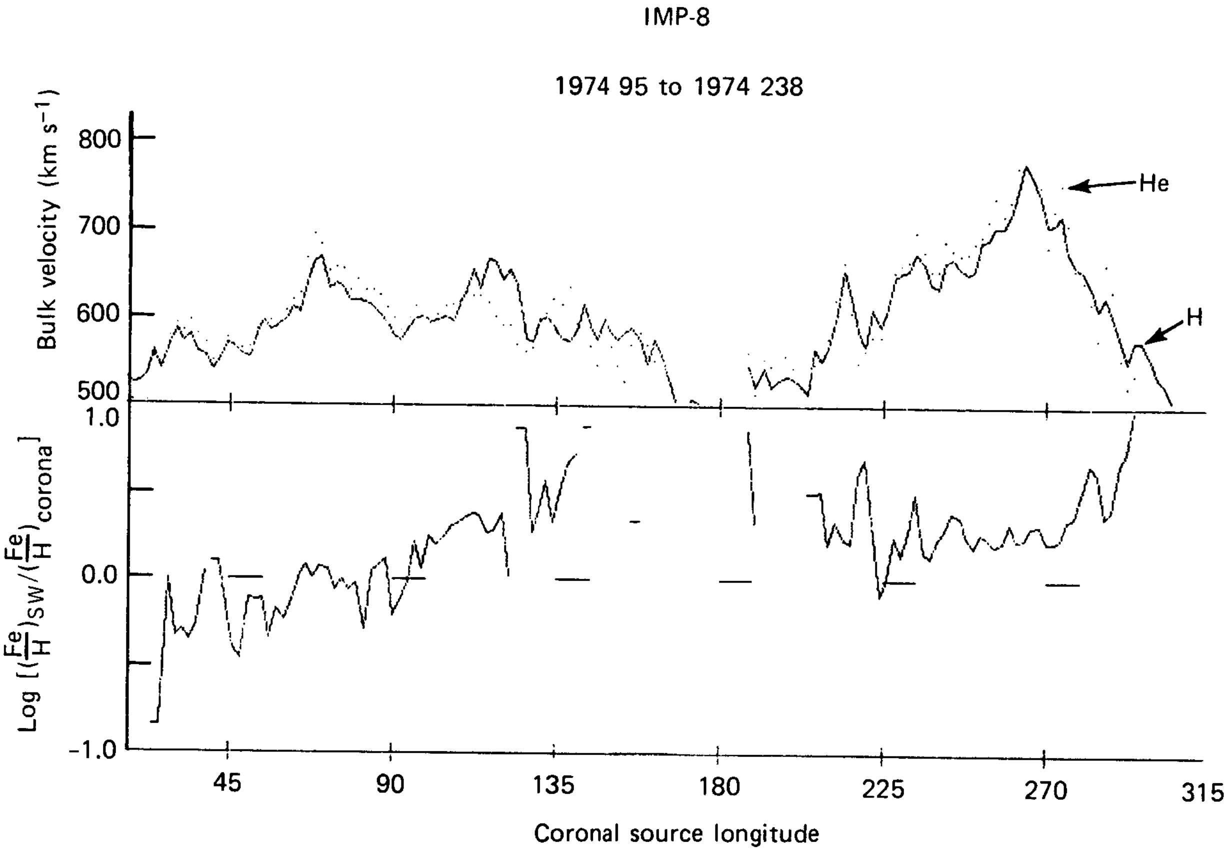

FIGURE 3 Average of velocities and Fe/H over 5 solar rotations in 1974, plotted versus source longitude.

LONG TERM TRENDS

Exploiting the repeatability of the corotating stream associated Fe/H ratios, in Figure 3 we average five consecutive solar rotations of data in mid-1974 to obtain a more continuous, representative longitude record of Fe/H than a single rotation with its attendant data gaps (due to the magnetospheric passes of the spacecraft) can provide. The stream on the right is fairly constant in Fe/H at a level lower by a factor of ~ 2 than the stream shown in Figure 2. The stream from 0° to 170° has a longitude-dependent Fe/H ratio, decreasing from a value a factor of ~ 2 above the stream centered at 260° to a value perhaps a factor of 3 below that value, for a total change of a factor of ~ 6 from one edge of the stream to the other. The stream between 0° and 170° is associated with the equatorward extension of the south polar coronal hole. We suggest here that the topology of the coronal source region may be related to the systematic decrease in Fe/H from west to east in this stream, in which the south-easterly orientation of the eastern boundary of the coronal hole allows us to sample the composition across the edge (which is not possible for the more usual meridional orientation). If this is the case, the implication is that Fe/H is higher for solar wind originating near the inner edges of the coronal hole boundary region, decreasing as one approaches the outer edge of the boundary region.

We have taken this process of summing over multiple rotations one step further. By summing over an entire year, and then taking estimates by eye of the minimum, maximum, and mean Fe/H values for each year, we can examine (Figure 4) the yearly trend in Fe/H over the four years 1973-1976 during the decline of sunspot Cycle 20. It is clear that there is a monotonic decrease in Fe/H over the period. There is also a decline in He/H over the same period (upper curve, data from Feldman et al., 1978), but the iron abundance decrease precedes the helium abundance decrease by at least a year. The difference between the trends in Fe/H and He/H is actually greater than Figure 4 portrays, since the iron data is all from high speed streams while the downturn in He/H is dominated by the low speed solar wind; in fact, Bame et al. (1977) reported that He/H at the higher speeds remained remarkably constant ($\sim 5\%$) over this same period in the maxima of high speed streams. Thus, we find that the iron and helium abundances in high speed streams differ in their behavior on both intermediate (one stream's duration) and long term (fraction of a year to fraction of a solar cycle duration) time periods, though they are sometimes well correlated on a fraction of a day time scale.

SUMMARY AND CONCLUSIONS

Using the 50 - 200 keV ion channel of a solid state detector on the EPE experiment, we have obtained the only thermal iron measurements at solar wind speeds over 600 km s^{-1} during the decline of Solar Cycle 20, when the solar wind structure was dominated by stable corotating coronal hole associated high speed streams. We have found that:

1) The response of the EPE to Fe, when compared to the LANL He measurements, is consistent with the iron bulk velocity, thermal velocity, and bulk flow angle being the same (on average) as those for helium.

2) The profile of Fe/H as a function of time or coronal source longitude is a stable, repeatable feature of a stable corotating high speed stream.

3) Fe/H within a corotating stream can vary significantly as a function of the plasma's coronal source longitude, up to a factor of ~ 6, and we have identified the edge of a coronal hole with a gradient in Fe/H.

4) A long-term decrease of a factor of ~ 4 is measured in Fe/H from 1973 to 1976 during the decline of solar cycle 20.

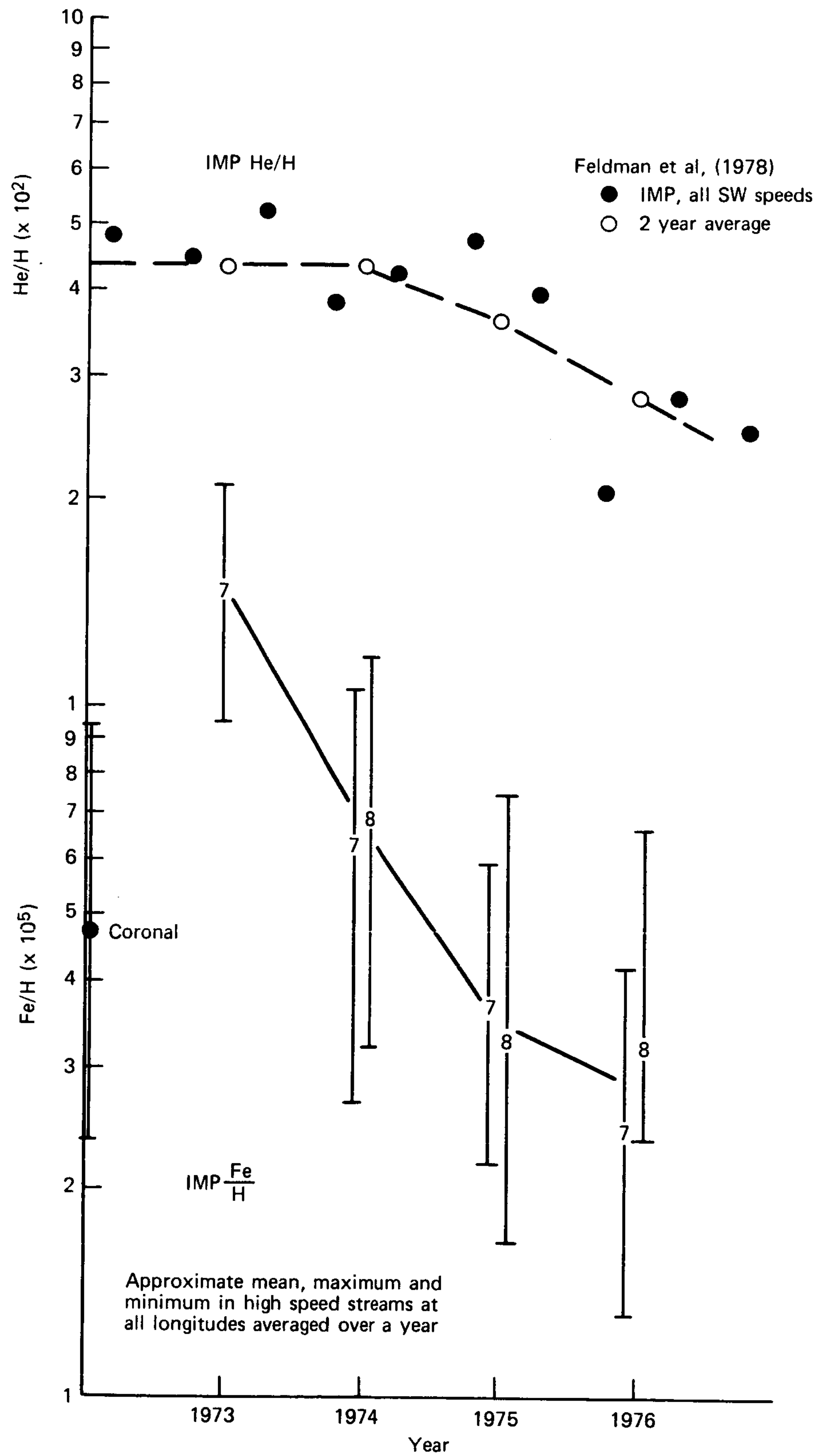

FIGURE 4 Four-year decrease in Fe/H during the decline of Solar Cycle 20.

ACKNOWLEDGEMENTS

We wish to thank D. J. Williams for the use of the IMP 7 and 8 EPE data, and R. D. Zwickl for his assistance with the LANL plasma data. Our effort was supported in part by NASA and in particular, at JHU/APL through Grant NAGW-264. The Air Force Geophysics Laboratory also provided partial support via Task ZF10 of Contract N00024-83-C-5301 between the U. S. Navy and The Johns Hopkins University.

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