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ABSTRACT

Solar wind velocities have been measured on a daily basis from data obtained by the Ames Research Center plasma analyzers on both Pioneer 10 and Pioneer 11. A comparison between the time profiles of the solar wind velocities observed at the two spacecraft shows that the solar wind has the same major features, such as high velocity streams, out to at least 5 astronomical units (AU) from the sun. Major features in the velocity time profile observed first at Pioneer 11 are seen later at Pioneer 10 with a delay consistent with the respective heliocentric longitudes of the two spacecraft, their radial distances from the sun, and the solar wind velocity. A more detailed comparison between the velocity measurements made at Pioneer 10 and Pioneer 11 shows that the range of solar wind velocities decreases with increasing radial distance from the sun. Although the average value of the solar wind velocity as measured over a sufficiently long period is approximately the same at both spacecraft, the deviations to higher and lower velocities are less at a greater radial distance from the sun. If one assumes for the purpose of providing a measure of the decrease in the velocity range that there is an exponential dropoff in the range of solar wind velocities as a function of radial distance from the sun, not until a distance possibly as great as 25 AU from the sun will the solar wind velocity variations be difficult to detect with the type of solar wind plasma analyzers on Pioneers 10 and 11. It appears that stream-stream interactions play a dominant role in preventing the classical radial expansion process in the solar wind. The result that the mean solar wind velocity remains approximately the same, but that the amplitude of the velocity variations decreases with increasing radial distance is consistent with there being an exchange of momentum between high speed and low speed solar wind streams as they interact and move outward from the sun.

INTRODUCTION

In this paper we are reporting a comparison between sets of solar wind velocity measurements made on a daily basis by the Ames Research Center Plasma Analyzer experiments on Pioneer 10 and Pioneer 11 in 1973. During this time period Pioneer 11 was between 1.0 and 2.7 astronomical units (AU) from the sun and Pioneer 10 was between 4.1 and 5.0 AU from the sun. The Pioneer 10 and Pioneer 11 solar wind plasma experiments are dual quadrispherical electrostatic analyzers utilizing two independent sets of 90 degree deflection plates for energy analysis. The higher resolution set has a mean radius of 9 cm with a 0.5 cm separation and uses 26 continuous channel multipliers as detectors, whereas the lower resolution assembly, with a mean plate radius of 12 cm and a 1 cm separation, deflects incoming particles into five current collectors connected to electrometer amplifiers. Both assemblies view along the spacecraft spin axis which is directed toward earth. The energy analysis for positive ions is provided for both sets of plates by stepping through a maximum of 64 equally logarithmically spaced plate voltage differences in synchronization with the spacecraft spin. The angular information is provided by the relative responses of the detectors as the spacecraft spins. For a more detailed description of the Pioneer 10 and 11 instrumentation see Wolfe et al. (1974).

The observations reported here have been made from real-time printouts of the solar wind data from Pioneers 10 and 11. In each instance one or more energy scans of data from either the high resolution or low resolution assembly were read to determine which energy step corresponded to the peak solar wind proton flux. From this the solar wind peak velocity was determined. These measurements were made once each day, when practicable, for both spacecraft and were spaced as nearly equally as possible.

Using two spacecraft to study the solar wind velocity at different distances from the sun aids in separating temporal variations from spatial variations. During the 200 day period of this study, the Pioneer 11-sun-Pioneer 10 angle decreased from 90° to nearly 0° and was less than 22° (about 1 3/4 days of solar rotation) for the latter half of this time. Gosling (1972) has shown for satellite separations of less than or equal to 2 days in a corotation sense (using Pioneer 6 and 7 interplanetary solar wind plasma data from 1969 and 1970) that the degree of correlation in the velocities is quite good, whereas for separations of 4 days or more the correlation is weak. For the second half of the 200 days covered in this study, the separation of Pioneers 11 and 10 is less than 2 days in the corotation sense and we can reasonably assume that differences in the solar wind velocity as observed at Pioneer 11 and 10 would evolve during the solar wind expansion and would not be due to temporal changes of coronal origin. Even in the first half of the 200 days of data where the corotation delay varied from about 7 days down to 2 days, an averaging over the long term would tend to emphasize the spatial variations, not the temporal. The great range in radial distance between Pioneer 11 and 10 is also a great advantage for studying radial variations. An earlier study of Neugebauer and Snyder (1966) from Mariner 2 data did not have the advantage of observations by two spacecraft over a large range of distance from the sun.

The Pioneer 10 measurements extend from May 3, 1973 to November 16, 1973, whereas the Pioneer 11 measurements were made between April 20, 1973 and November 6, 1973. Figure 1 shows the ecliptic plane projections of the orbits of Pioneers 10 and 11 and their relative positions for the beginning, middle, and end of the period during which the data were taken.

COMPARISON OF PIONEER 11 AND PIONEER 10 VELOCITY OBSERVATIONS

The first half of the 200 days of solar wind velocity data for Pioneers 10 and 11 is plotted in Figure 2. Each 25-day segment of the Pioneer 11 velocity time-profile is compared with a 25-day segment of the Pioneer 10 velocity time profile. A 25-day interval is the approximate synodical period of rotation of the solar equator with respect to the Pioneer spacecraft. The angular velocities of the spacecraft about the sun decrease rapidly as the radial distance from the sun increases; so that the synodical rotation period of the solar equator soon becomes quite close to the period of rotation in a fixed heliocentric frame of reference. Since data gathered shortly after the Pioneer 11 launch are used here, this period is actually somewhat too short at the beginning. However, approximately 100 days after launch, the synodical period has already decreased to about 25.5 days. It should be stressed, however, that the analysis presented in this paper does not depend upon the solar synodical rotation period.

By breaking the display of data into 25-day segments, the persistance of high speed streams for several solar rotations is readily shown. The Pioneer 10 segment of data in each case is delayed by the time to the nearest whole number of days that it would take for the sun to rotate through the Pioneer 11-sun-Pioneer 10 angle for midway through the Pioneer 11 time interval plus the time it would take for the solar wind to traverse the radial distance from Pioneer 11 to Pioneer 10 at the average velocity observed at Pioneer 11 for those 25 days. Velocities observed at Pioneer 11 which are greater than the 200-day average velocity are shaded in Figure 2. Similarly Pioneer 10 measured velocities exceeding the 198-day average are also shaded. Only 198 days of Pioneer 10 data are used because the average solar wind delay time from Pioneer 11 to Pioneer 10 decreased from 13 to 11 days between the first 100 and second 100 days of observation.

From an examination of the plots shown in Figure 2 it is clear that the same general pattern of peaks and valleys in the velocity time profile is seen at both Pioneers 11 and 10 with a delay approximately equal to that appropriate to their respective heliocentric longitudes and radial distances from the sun. It is important to note, however, that the Pioneer 10 measurements have much less amplitude variation than those of Pioneer 11 with less range to both high and low solar wind velocities. This feature of the data is shown readily in the histograms of Figure 3. For this plot the daily velocity measurements presented in Figure 2 have been grouped into 25 km/sec wide intervals for both Pioneer 10 and Pioneer 11. A linear interpolation has been made between neighboring velocity measurements to determine a velocity value for those days when no data were available. This procedure introduces trivial error and affords a more complete comparison between the two sets of data. The period of time for the Pioneer 10 measurements is delayed 13 days with respect to the Pioneer 11 time period. This is approximately the average delay for this 100 day interval as calculated from the heliocentric longitudes of the two Pioneer spacecraft, their respective radial distances and the average solar wind speed observed. There are 18 daily velocity measurements above 675 km/sec for Pioneer 11, whereas for Pioneer 10 there are none. Also the Pioneer 11 measurements show 8 daily velocity samples below 350 km/sec, whereas Pioneer 10 has none. Thus, the Pioneer 11 velocities have a much greater range than those of Pioneer 10 for this period.

In order to compare the relative smoothness of the velocity profiles observed at Pioneers 10 and 11, the changes in velocity from the previous day's measurement are given in the histogram shown in Figure 4. The intervals for the velocity changes are 20 km/sec wide. It is readily seen that the day-to-day velocity changes measured at Pioneer 10 have a smaller range than those observed at Pioneer 11. It is clear that the velocity time profile observed at the greater radial distance from the sun is smoother than that seen closer to the sun.

The second half of the 200 days of solar wind velocity observations from

Pioneers 10 and 11 is plotted in Figure 5 in the same manner as was the first half of the data presented earlier in Figure 2. The average velocity observed for the second 100 days is considerably lower than that observed for the first 100 days. The average velocity observed by Pioneers 10 and 11 for the first 100 day interval was 512 km/sec, whereas during the second 100 day interval the observed average velocity was only 425 km/sec. This is also evident in the plot of Figure 5, because there are few measurements greater than the 200-day average (Pioneer 11) or 198-day average (Pioneer 10) shown by the shaded in areas of the velocity time profiles. The day-to-day velocity variations seen at both Pioneers 10 and 11 are smaller during these second 100 days in comparison with the first 100 days. The same general pattern, however, of peaks and valleys in the velocity time profile is seen as before at both Pioneers 10 and 11 with approximately the appropriate delay. Again the measurements made at the greater radial distance from the sun by Pioneer 10 have less amplitude variation than those made closer to the sun at Pioneer 11. Figure 6 shows histograms of the Pioneer 10 and 11 velocity measurements which are presented in Figure 5. There are 8 daily velocity measurements from Pioneer 11 which are below 300 km/sec, whereas for Pioneer 10 there are none. Also there are 15 velocities greater than 525 km/sec in the Pioneer 11 data versus 8 in the Pioneer 10 data. Thus, as in the first half of the data, the Pioneer 11 velocities have a greater range in amplitude than those of Pioneer 10. Again, in order to compare the relative smoothness of the velocity time profiles observed at the two spacecraft for this period, the changes in velocity from the previous day's measurement are given in the histogram shown in Figure 7. The intervals are the same as those in Figure 4. Again, it is evident that the day-to-day velocity changes are smaller on the average and have a smaller range at the greater radial distance from the sun as observed at Pioneer 10 in comparison with the Pioneer 11 observations at a lesser radial distance.

In order to make some sort of extrapolation from these data and get a feeling for how the solar wind velocity fluctuations are damping out with radial distance, we have computed the exponential rate of decay of the velocity amplitudes measured at Pioneers 10 and 11 from each 100-day set of data. Table 1 shows these results. For each spacecraft the time averaged value for the radius from the sun was calculated for the 100-day period. Also, the range of the daily velocity samples, excluding the highest and lowest 5%, was determined for the measurements made at Pioneers 10 and 11. From these values the distance for 1/e decay was calculated. The distance at which this velocity range would be reduced to 20 km/sec assuming the exponential decay was then determined. This distance is approximately 25 to 30 astronomical units. For the Pioneer 10 and 11 solar wind plasma analyzers, a velocity difference of 20 km/sec corresponds approximately to the difference in velocity for protons detected in adjacent energy steps when the instrument is in its highest energy resolution mode. Therefore when the velocity range is of this order, the instrument, to first order, will see little velocity variation.

CONCLUSIONS

It is clear that the velocity amplitudes in the solar wind stream structure decrease dramatically with increasing radial distance from the sun. What is not clear, however, is the rate of this velocity amplitude decrease. One might expect, for example, that a 1/e decay rate for the stream velocity amplitudes is too large since stream-stream interactions become less important with decreasing amplitude and require a greater radial distance to interact. This is somewhat evidenced by comparing the lower amplitude velocity variations seen in the second 100 day observations as contrasted to the first 100 days presented here. On the other hand charge exchange between the solar wind and the influx of interstellar gas will almost certainly remove kinetic energy from the solar wind and tend to drastically increase the effective solar wind temperature. The radial distance at which interstellar interactions may play a key role in altering the solar wind expansion process can not be ascertained at this time. Due to the long term statistical fluctuations in the data it was not possible to determine the decay rate more precisely by dividing the 200 days of observations into more than just two 100 day intervals.

In any event, it is not until far beyond the orbit of Jupiter that the solar wind is expected to attain a constant velocity radial expansion state. It appears that stream-stream interactions play a dominant role in preventing the classical radial expansion process in the solar wind. The result that the mean solar wind velocity remains approximately the same, but that the amplitude of the velocity variations decreased with increasing radial distance, is consistent with there being an exchange of momentum between high speed and low speed solar wind streams as they interact and move outward from the sun. It is hypothesized that the stream-stream interactions, at least between 1 and 5 AU, produce scattering centers which will prevent the observation of a significant galactic cosmic ray gradient in this region of space. In addition, the exchange of momentum between fast and slow solar wind plasma is probably not perfectly elastic and therefore non-adiabatic expansion might be expected due to the generation of waves and turbulence.

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TABLE 1.

A COMPARISON OF PIONEER 10 AND 11 SOLAR WIND VELOCITY DISTRIBUTIONS AT DIFFERENT RADIAL DISTANCES FROM THE SUN

SPACECRAFT	PERIOD (1973), days	RADIAL RANGE TRAVERSED, AU	AVERAGE RADIUS, AU	RANGE OF MIDDLE 90% OF VELOCITIES, km/sec	RADIAL DISTANCE FOR 1/e DECAY, AU	DISTANCE WHERE RANGE OF MIDDLE 90% OF VELOCITIES ≅ 20 km/sec, AU
PIONEER 11	110-209	1.05 TO 1.81	1.38	395	7.8	25
PIONEER 10	123-222	4.09 TO 4.57	4.33	270		
PIONEER 11	210-309	1.82 TO 2.68	2.25	286	10.5	30
PIONEER 10	221-320	4.57 TO 4.97	4.77	225		

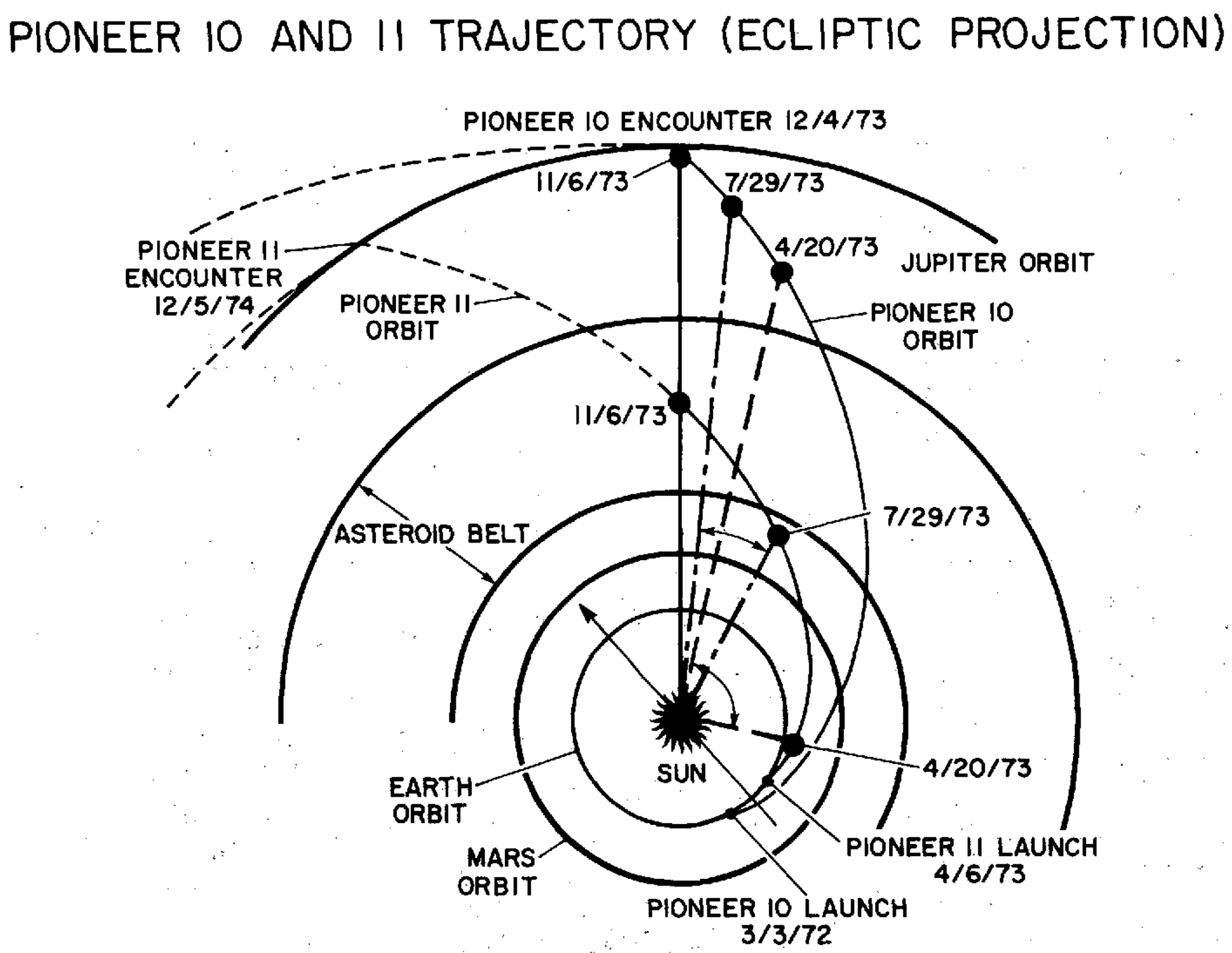

Figure 1. Pioneer 10 and 11 trajectory (ecliptic projection) indicating spacecraft positions and angles between spacecraft-sun lines for beginning, middle, and end of period when solar wind velicity data were obtained.

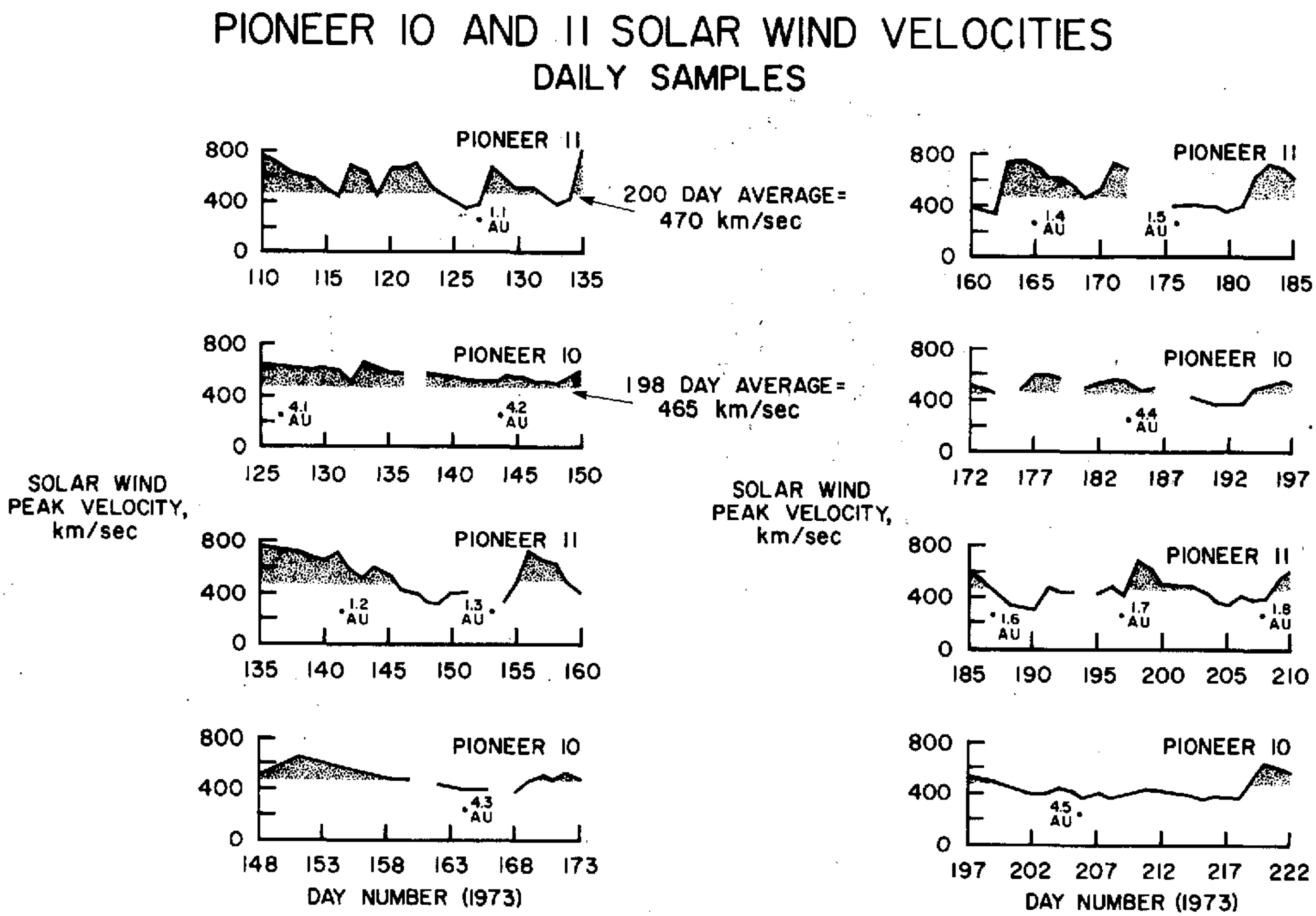

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Figure 2. Comparison of Pioneer 10 and 11 daily solar wind velocity measurements for first 100 days of data. For each 25-day segment the Pioneer 10 measurements are shifted by the time appropriate for the angle between spacecraft-sun lines and different spacecraft-sun distances.

PIONEER 10 AND 11 SOLAR WIND
DAILY SAMPLES

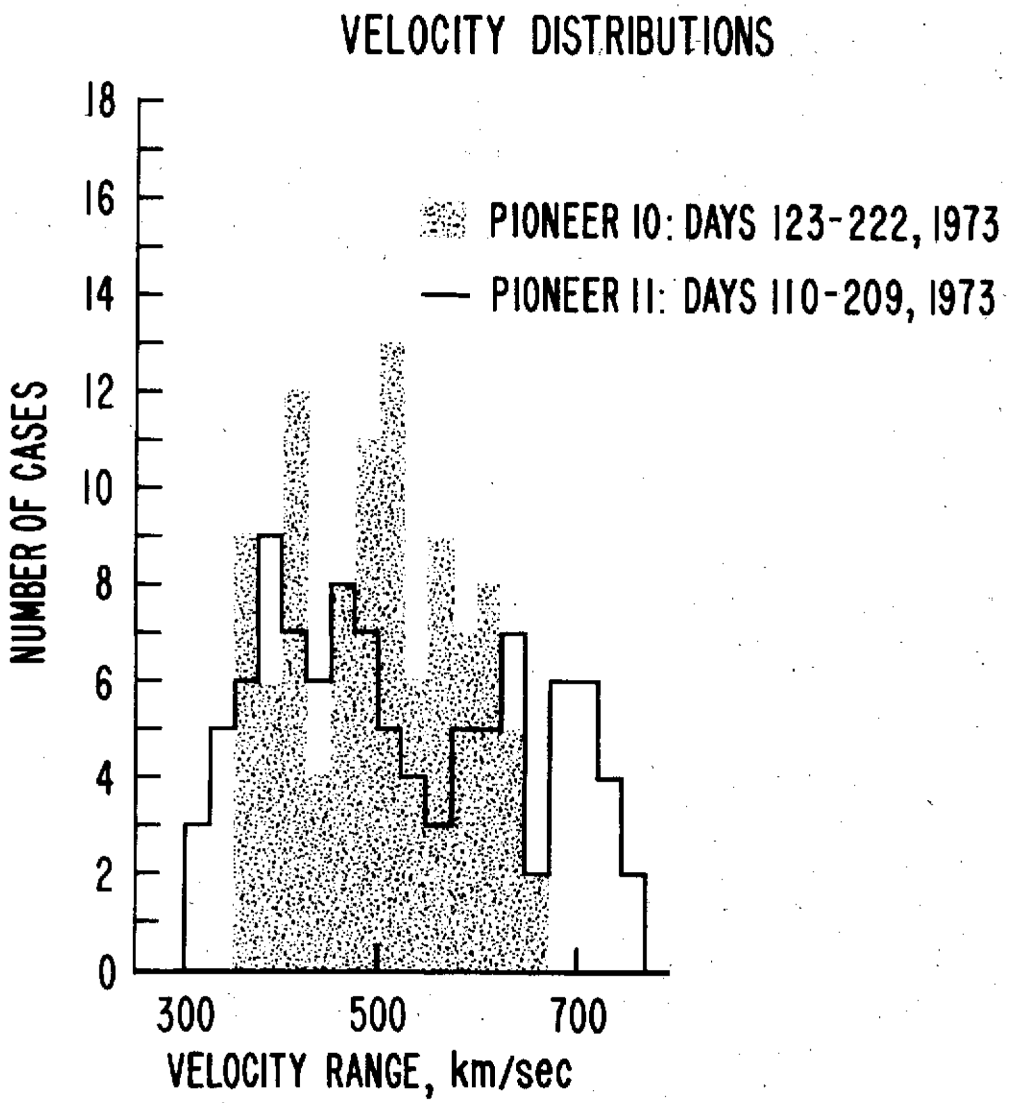

Figure 3. Histogram of Pioneer 10 and 11 daily solar wind velocity measurements for first 100 days of data. Intervals for histogram plotting are 25 km/sec.

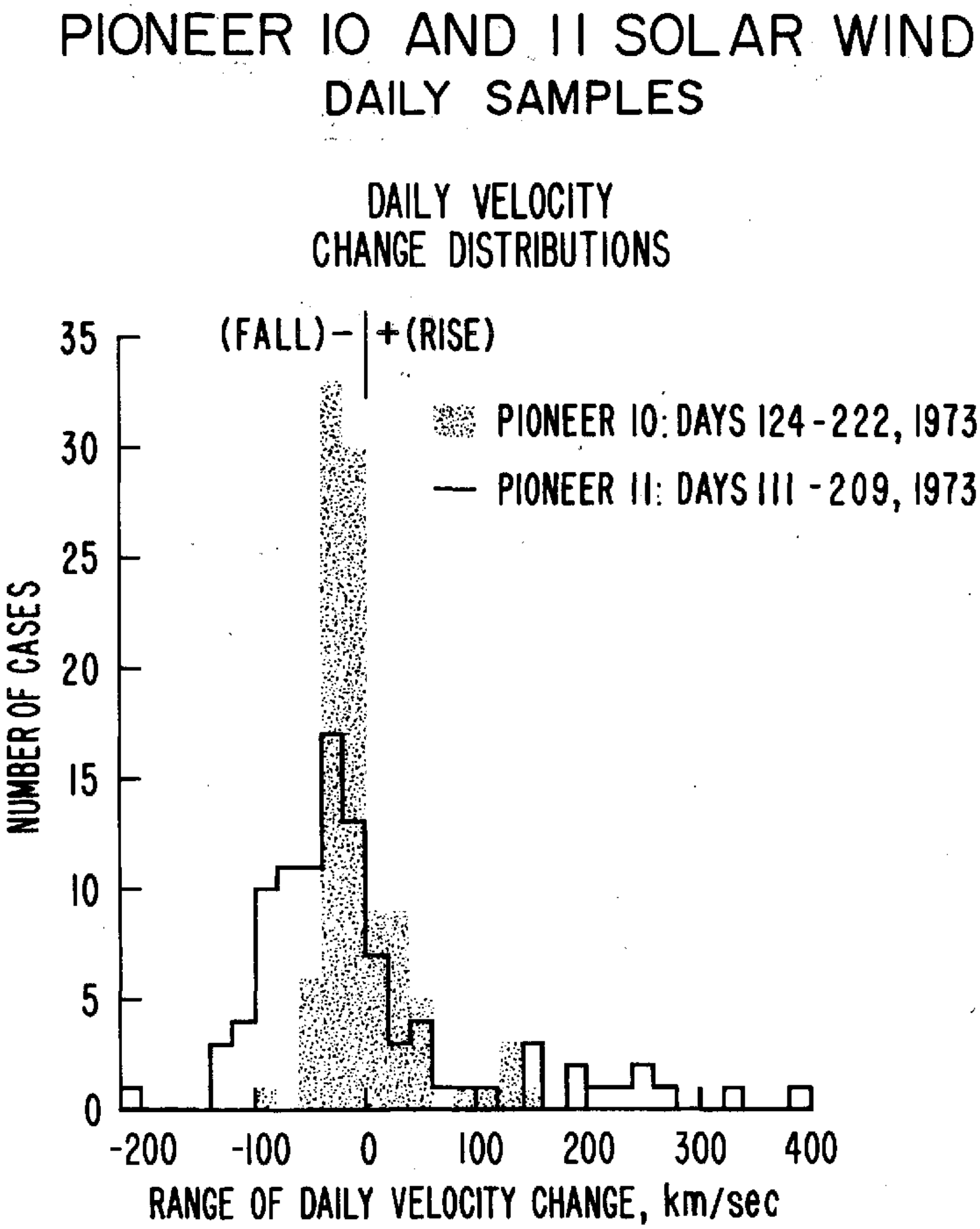

Figure 4. Histogram of differences between daily solar wind velocity measurement and previous day's measurement for Pioneers 10 and 11 for first 100 days of data. Intervals for histogram plotting are 20 km/sec.

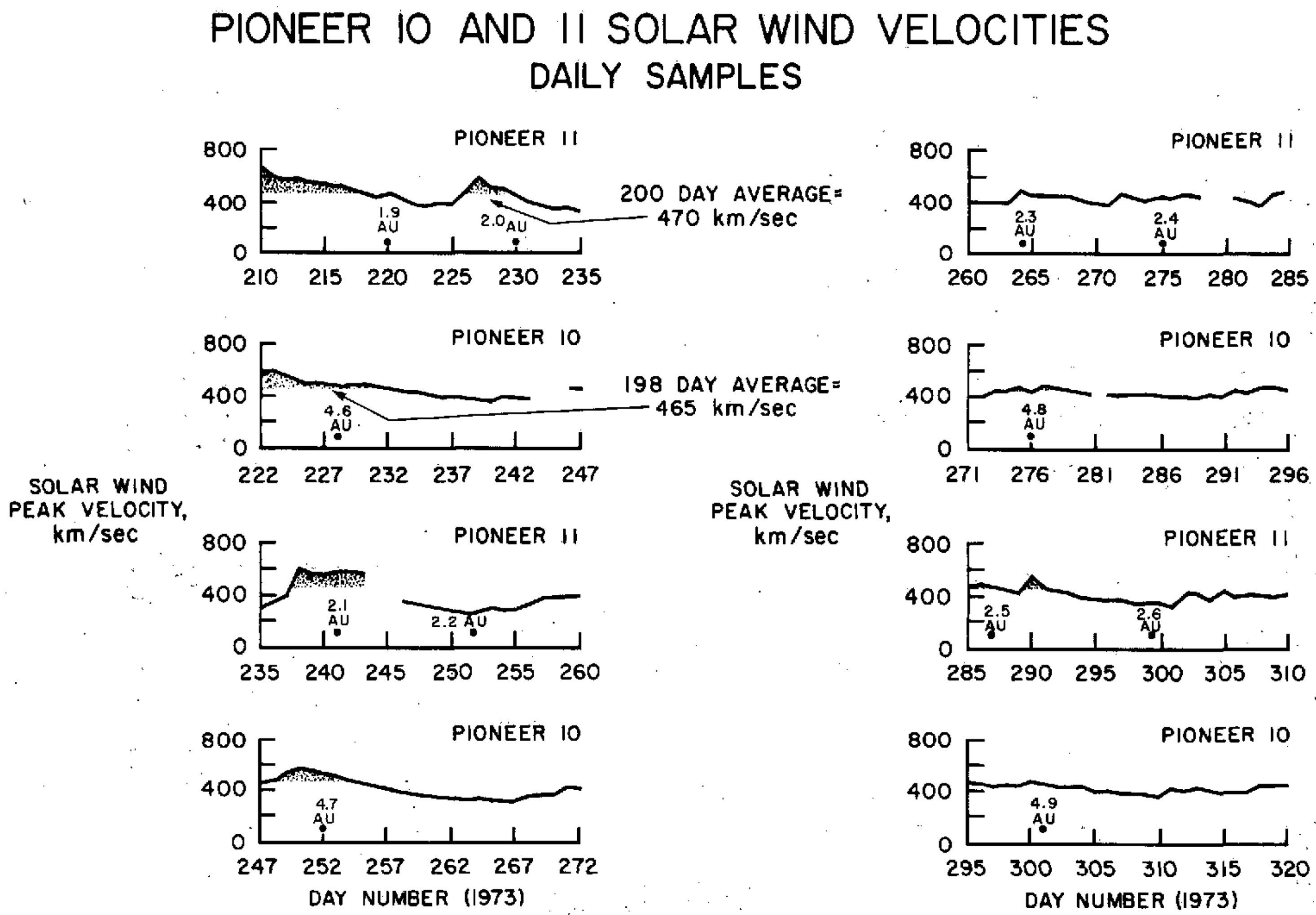

Figure 5. Comparison of Pioneer 10 and 11 daily solar wind velocity measurements for last 100 days of data. For each 25-day segment the Pioneer 10 measurements are shifted by the time appropriate for the angle between spacecraft-sun lines and different spacecraft-sun distances.

PIONEER 10 AND 11 SOLAR WIND
DAILY SAMPLES

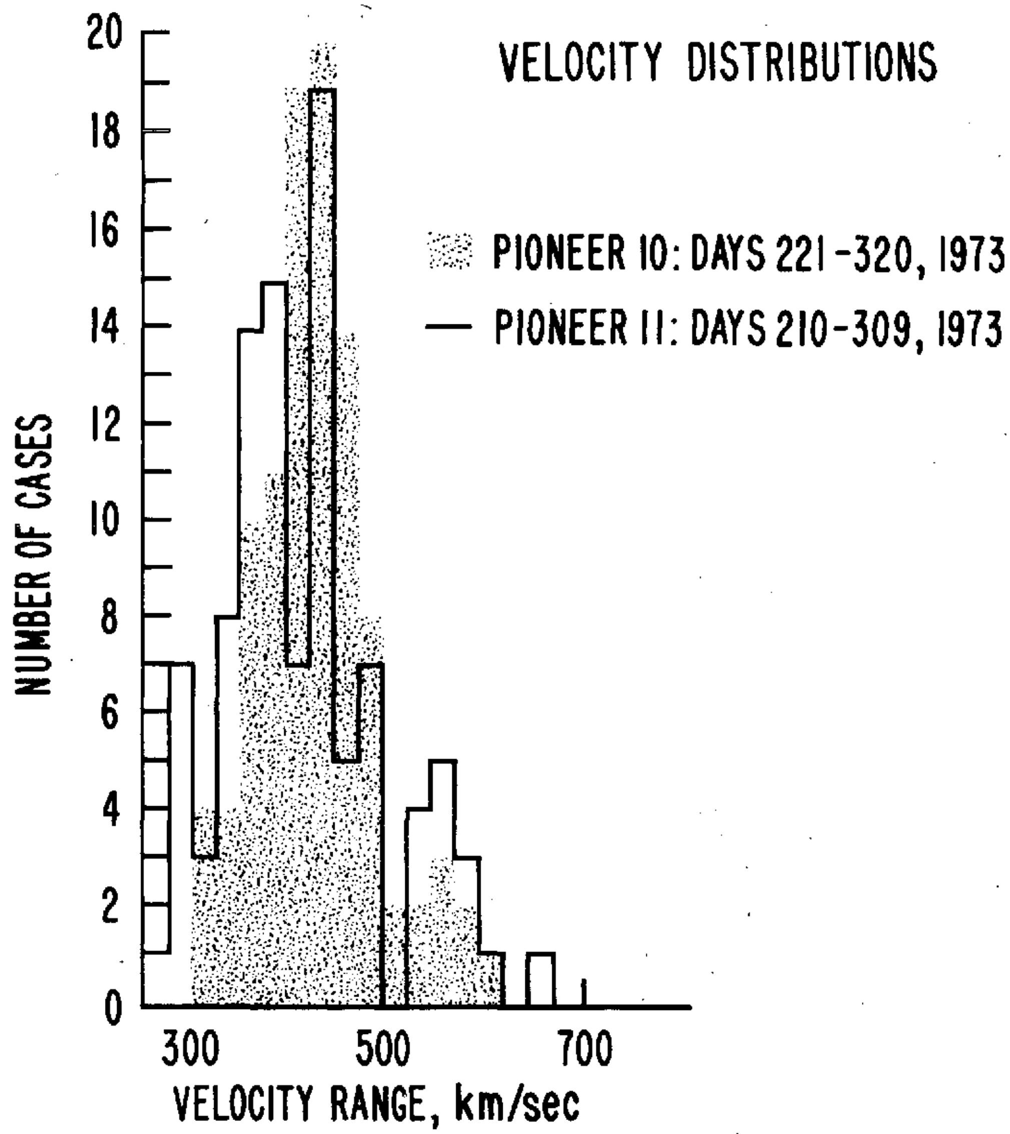

Figure 6 Histogram of Pioneer 10 and 11 daily solar wind velocity measurements for last 100 days of data. Intervals for histogram plotting are 25 km/sec.

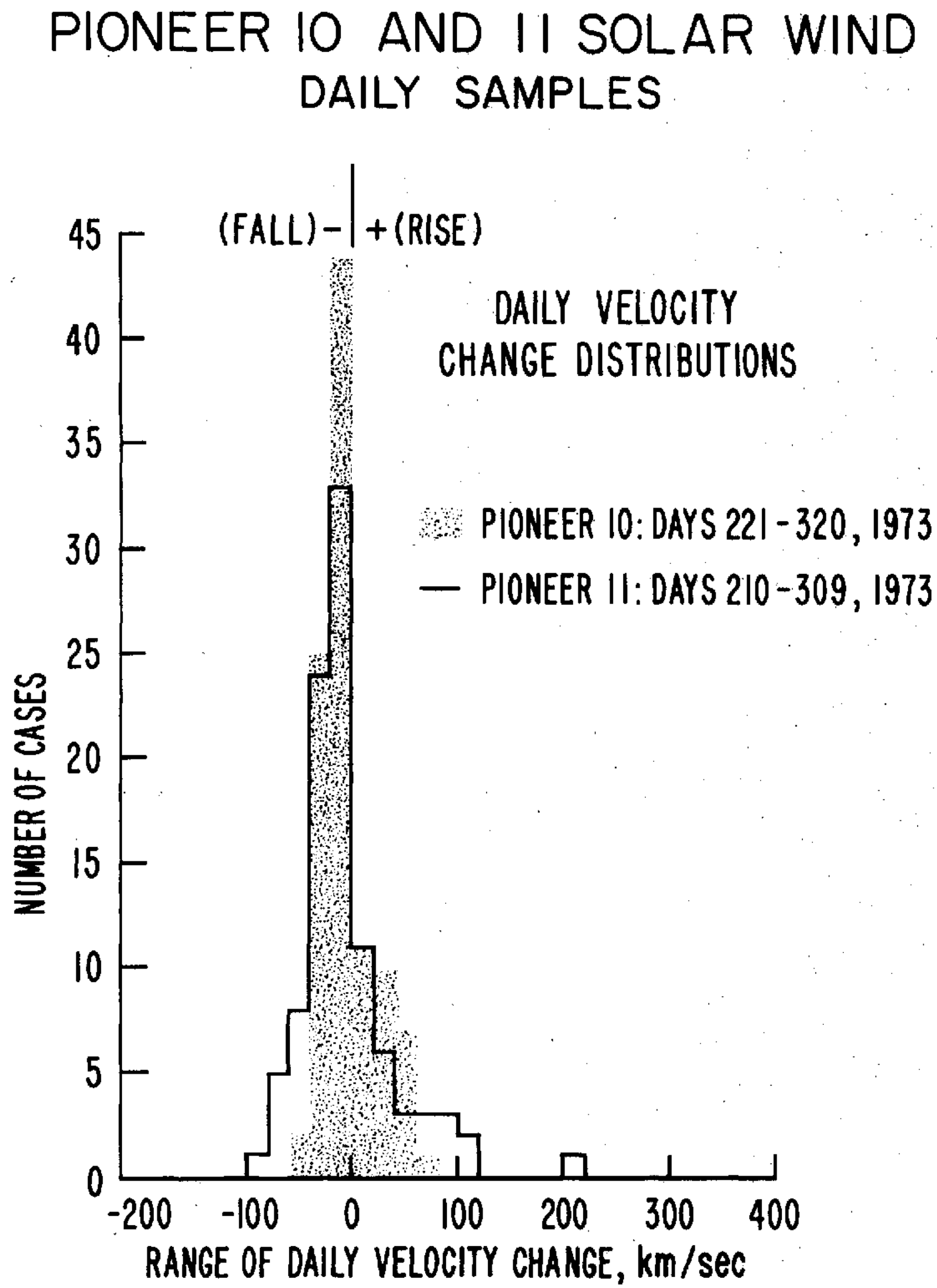

Figure 7 Histogram of differences between daily solar wind velocity measurement and previous day's measurement for Pioneers 10 and 11 for last 100 days of data. Intervals for histogram plotting are 20 km/sec.