High-Speed Streams and Co-Rotating Interaction Regions in the Solar Wind

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1. Introduction

The solar wind is rarely observed to be the steady-state spherical outflow predicted by simple one-dimensional analysis. Not only does the solar magnetic field induce fluid inhomogeneities in the corona and surrounding interplanetary medium, but dynamical processes such as rotation, convection, and flare and filament eruption also produce a rich array of non-steady structure in the wind. This review will concentrate on one important class of such transient fluid phenomena: the co-rotating high-speed stream. These relatively long-lived spatial structures have been observed from heliocentric distances of 0.3 to 40 AU, and over heliocentric latitudes spanning 40° about the ecliptic. The flow speed in these streams can often be as high as 700 to 800 km/s, and their radial evolution produces a complex dynamical interaction with the ambient wind (which has a slower radial velocity, 300 to 400 km/s), often by compressing and rarefying the surrounding medium. Structures exhibiting such rotationally-induced (and magnetohydrodynamic) effects are called "co-rotating interaction regions" (CIR's), and have been the focus of a great deal of research.

A summary of the observational evidence for CIR's in the solar wind will be given in § 2. The current state of theoretical understanding of these phenomena will be presented in § 3, focusing on the origins of CIR's (§ 3.1) and their dynamical evolution (§ 3.2). Finally, concluding remarks in § 4 will deal with the implications of the presence of CIR's in the solar wind on their possible existence in stars of other spectral types.

2. Observational Evidence

Although some indirect evidence for the existence of CIR's has been obtained from earth-based observations, the vast majority of the data comes via *in situ* spacecraft observations. The first detection of well-resolved regions of high-speed wind velocity was from Mariner 2 (Snyder and Neugebauer 1964), and some of the data is shown in Figure 1. Typical streams begin with a relatively abrupt rise in the flow speed, which trail off slowly on timescales of 3-5 days. Also, many of the streams tend to recur on an interval commensurate with the solar rotation period ($\sim$ 27 days), which implies their existence as co-rotating spatial structures.

Subsequent observations have confirmed this basic picture. Neugebauer and Snyder (1967) showed that the density "piles up" on the leading edge of a stream, and is followed by a region of relatively low density on the trailing edge. The Helios spacecraft measured high-speed streams

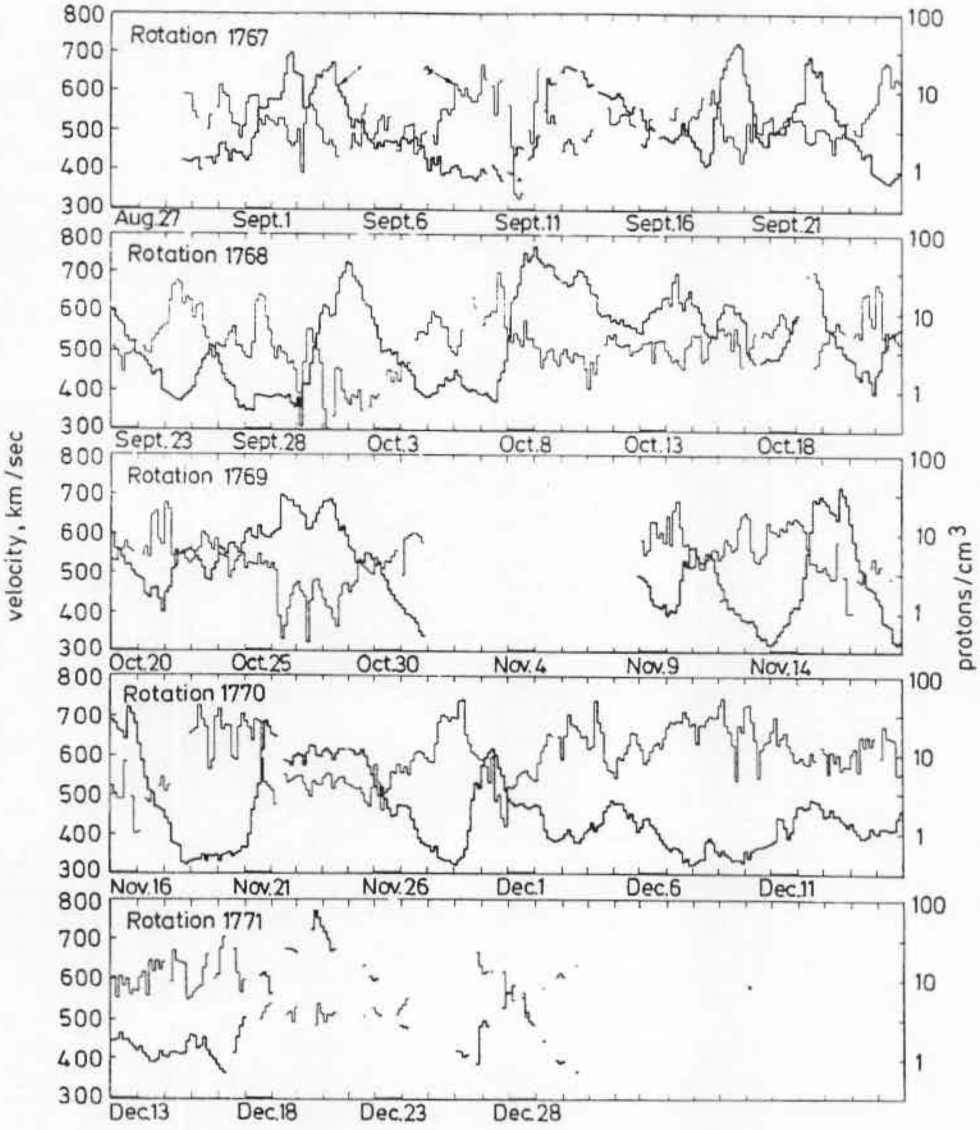

Fig. 1.— Three-hour averages of the solar wind proton density (light lines) and flow speed (heavy lines) observed by Mariner 2 in 1962. The time coordinate has been broken into 27-day solar rotation periods (Neugebauer and Snyder 1966; Hundhausen 1972).

as close to the sun as 0.3 AU (Schwenn et al. 1978), and found thin ($\sim 10^\circ$) latitudinal extent of CIR's near the plane of the ecliptic. The Pioneer and Voyager spacecraft enabled the radial evolution of streams to be measured, and predictions that the non-linear nature of the flow leads to (i) co-rotating shocks at about 2-3 AU (Gosling, Hundhausen, and Bame 1976; Smith and Wolfe 1977), and (ii) complex interactions of several streams at still larger heliocentric distances (Burlaga 1984; Whang and Burlaga 1986), have been confirmed.

Before continuing to investigate the solar origins of these structures, the CIR phenomenon itself should be properly distinguished from some of the other time-variable structured features observed in the solar wind. First, Iucci et al. (1980) distinguish between "regular" and "complex" high-speed streams, where the former type is associated with coronal holes diverging from relatively quiet solar regions, and the latter is associated with active regions with flare activity, which exhibit a high degree of variability. Thus, the complex high-speed stream begins to merge with the phenomenon of a flare-produced shock wave, although such shocks are not often observed to recur with solar rotation (cf. Hundhausen, Bame, and Montgomery 1970). Interplanetary filaments are co-rotating "directional discontinuities" in magnetic field, but with little or no variations in the pressure or density of the gas (Burlaga and Ness 1969). However, these filaments are often associated with tangential wind velocity shears (Siscoe, Turner, and Lazarus 1969), which share some of the dynamical features of CIR's.

The wind expansion from coronal holes has been long associated with "regular" high-speed stream flow (see, e.g. the first definitive correlations from Skylab X-ray data by Krieger et al. 1973). Measurements of both interplanetary magnetic field variations (Levine 1978) and cosmic ray intensity signatures (Venkatesan, Shukla, and Agrawal 1982) seem to confirm this paradigm. It is thus possible, given an observed photospheric distribution of radial magnetic field, to predict the coronal and interplanetary field characteristics, and thus the regions and times of most probable CIR generation. Hundhausen (1972) reviews this technique (using a standard "source surface" model assuming the field is derivable from a scalar potential) in his § V.6, and finds general agreement with the locations of observed streams.

One final observational signature of CIR's that needs to be noted is their correlation with the "sector structure" of the interplanetary magnetic field. The polarity of the field tends to point either outwards or inwards along co-rotating spirals in quite long and alternating intervals (with often 2-4 sectors around the ecliptic, cf. Wilcox and Ness 1965; Burlaga 1984). This structure in the ecliptic plane is thought to be a projection of an overall "warped heliospheric current sheet" generated by the approximate dipole nature of the sun's magnetic field, which is tilted with respect to the ecliptic (see Figure 2). Measurements from the spacecraft Imp 1, Imp 3, and Vela 3 have shown a marked correlation between the location of high-speed streams and the magnetic sectors (Wilcox and Ness 1965; Ness, Hundhausen, and Bame 1971). This organization of the flow with respect to the interplanetary magnetic field seems to agree with the above interpretation of individual streams originating from coronal holes of well-defined polarity. Also, the geomagnetic phenomenon of "M-regions" (relatively long-lived solar-terrestrial activity observed to recur on solar rotational

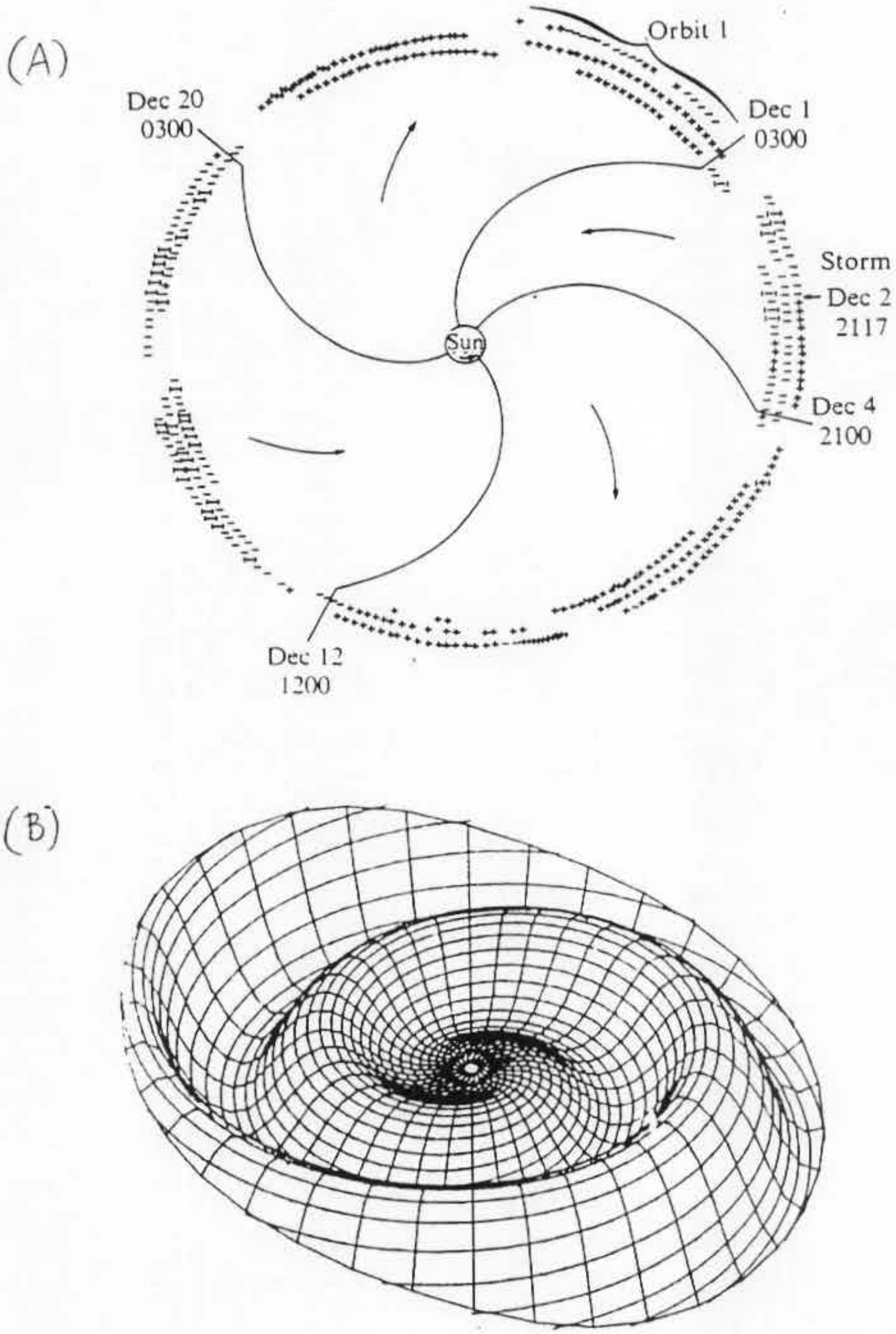

Fig. 2.— (A) Three-hour averages of the magnetic polarity pattern observed by Imp 1 in the plane of the ecliptic (Wilcox and Ness 1965; Hundhausen 1972). (B) The structure of the current sheet expected for an oblique rotator (Sakurai 1985).

timescales) is explainable as the passage of the earth through these magnetic sector related streams (cf. Hundhausen 1977).

3. Theory of CIR's

3.1. Origins

Asymmetries in the coronal magnetic field seem to be the major contributory factor to the initial generation of CIR streams. Thus, any theoretical investigations into the origins of high-speed wind flows must deal with magnetohydrodynamics (MHD) in the inner and outer corona. Global MHD models, such as those of Pneuman and Kopp (1971), can calculate the distortion of simple sub-coronal magnetic field configurations by a wind. Figure 3 (from Pneuman and Kopp 1971) shows the effect of an isothermal corona on a rotationally-aligned dipole magnetic field at $r = R_\odot$, using the frozen field approximation, and the familiar "helmet streamer" structure becomes evident. Note, however, that the contrast between the polar (coronal hole) and equatorial (close field-line, near the neutral sheet) wind velocities from this model is small – 130 km/s versus 110 km/s at $r = 5R_\odot$, respectively.

More progress can be made if one restricts the spatial domain of the model from the entire sun to a relatively isolated coronal hole. Kopp and Holzer (1976) considered a quasi-one-dimensional case, where the cross-sectional area $A(r)$ of MHD flux tubes is constrained to diverge faster than the purely radial r^2 divergence, via the mass continuity equation,

$$\frac{d}{dr}(\rho v_r A) = 0 \ , \qquad A(r) = A(R_\odot)\left(\frac{r}{R_\odot}\right)^2 f(r) \ , \tag{1}$$

where f is an arbitrary "spreading factor." Thus, the magnetic field equations can be ignored, and the problem treated purely hydrodynamically. Although significant departures are found from the familiar Parker (1958, 1963) solar wind flow, Kopp and Holzer's different non-spherical divergence models all result in the same terminal speed ($\sim$ 600 km/s) because of the conservation of total energy in the wind. Suess (1979) reviews further developments in these general models, and reaches the conclusion that simple pressure-driving and thermal conduction, even with diverging field lines, are not sufficient to explain the observed velocities and densities in CIR flows.

Currently, two mechanisms have been proposed that may provide the necessary energy and/or momentum deposition to account for the observed high-speed streams: (i) hydromagnetic waves, and (ii) diamagnetic acceleration. The Mariner 2 probe detected outward propagating Alfvén waves near $\sim$ 1 AU (Belcher and Davis 1971), but the question is whether these waves can deposit enough power into the supersonic wind. Leer, Holzer, and Flå (1982) review the physics of the interaction between Alfvén waves and the solar wind, in the short-wavelength (WKB) approximation. The

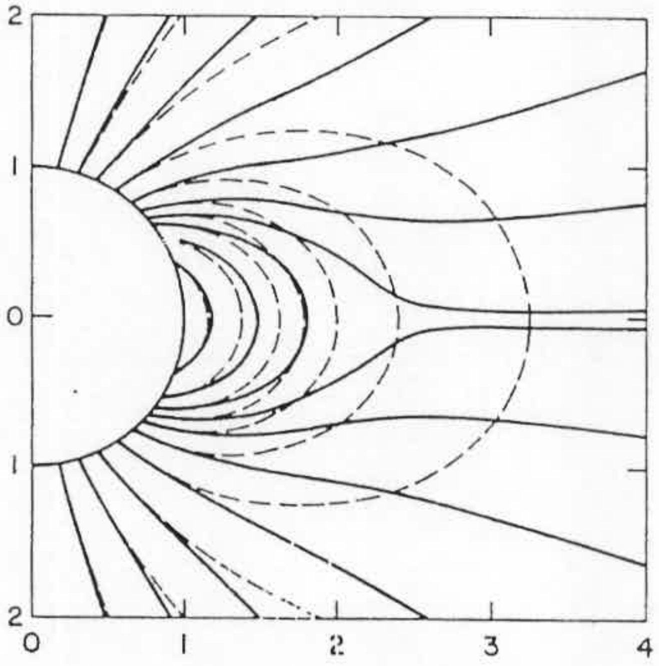

Fig. 3.— Field and streamline distribution (solid lines) corresponding to the base conditions in which the normal component of the magnetic field is that of a dipole (dashed lines), and the reference density is independent of latitude (Pneuman and Kopp 1971).

added Lorentz force per unit mass is given in the radial direction by

$$F_w = \frac{1}{\rho}\frac{d}{dr}\left(\frac{<\delta B^2>}{8\pi}\right) \ , \tag{2}$$

where $<\delta B^2>$ represents an r.m.s. field perturbation by the waves. Although solutions for the mean square wave velocity,

$$<\delta v^2> \ \approx \ <\delta B^2> /4\pi\rho \tag{3}$$

(in the WKB limit) can be found that provide the necessary energy and momentum at 1 AU, the resulting values of $<\delta v>$ are both extremely tightly constrained and large enough ($\sim 20-30$ km/s) to produce un-observed Doppler shifts in the corona and interplanetary medium. More recently, however, advanced models of waves (with a wavelength of the same order as the width of their associated coronal hole) show that coronal holes can act as "leaky wave guides" which transport energy flux outward into the wind in a highly geometry-dependent manner (Davila 1985; Cally 1987). Clearly much more needs to be learned about the MHD effects of waves in expanding plasmas.

An alternate theory of energy and momentum deposition was originally proposed by Schlüter (1957), wherein small bubbles of plasma from the photosphere or chromosphere get injected into the corona, thus distorting the ambient magnetic field and adding energy to restricted spatial regions. Pneuman (1986) extends this simple "melon seed" paradigm, and proposes convection as a possible initial impulse. Also, the high conductivity of the ambient coronal field results in field lines being pushed aside when the bubble moves upward – hence the name "diamagnetic acceleration." Pneuman finds that terminal velocities of ~ 1200 km/s can be reached by the flow that is affected by such motions, but ignores the possibly important effects of turbulent mixing in the supersonic wind.

3.2. Dynamical Evolution

Once a perturbation to the velocity, density, or pressure of the ambient solar wind has been generated in the corona, it propagates outward obeying the MHD conservation equations. In the inviscid, polytropic, and infinite-conductivity limit, these equations can be written (see, e.g. Hundhausen 1972; Jackson 1975)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \ , \tag{4}$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{\rho}\nabla P - \frac{1}{4\pi\rho}\mathbf{B}\times(\nabla\times\mathbf{B}) + \mathbf{g} \ , \tag{5}$$

$$\frac{\partial}{\partial t}(P\rho^{-\gamma}) + (\mathbf{v}\cdot\nabla)(P\rho^{-\gamma}) = 0 \ , \tag{6}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}) \ , \quad \nabla\cdot\mathbf{B} = 0 \ , \tag{7}$$

where the fluid velocity $\mathbf{v}$, the mass density ρ, the gas pressure P, and the magnetic field $\mathbf{B}$ are functions of position and time. The gravitational acceleration $\mathbf{g}$ and the polytropic exponent γ are assumed known, and an ideal gas equation of state,

$$P = \frac{\rho k(T_e + T_i)}{\mu m} \tag{8}$$

where k is Boltzmann's constant and μm is the mean mass of the ionized gas particles, is utilized.

Until recently, most all of the solutions to the dynamical equations for high-speed stream flow have assumed that the dominating physics is in the purely *hydrodynamic* advection of material into the interplanetary medium. This "snowplow" paradigm considers the fact that a high-speed plasma overtaking a low-speed plasma produces compression, which eventually steepens into a shock, and that the intrinsic thermodynamic and magnetic (i.e. pressure force) components of the fluid play a relatively minor role. Linear perturbation analysis of the hydrodynamic equations (Carovillano and Siscoe 1969; Siscoe and Finley 1972) confirm this basic picture in models inside ~ 1 AU, but cannot be applied exterior to this, where non-linear steepening and shock formation begin to occur.

The simple one-dimensional non-linear models of Hundhausen (1973) are worthy of note due to a relatively detailed fit to the observations of CIR's with the Vela 3 spacecraft. This model assumed a completely radial wind flow in the equatorial plane, which is valid in the limit $|v_\phi| \ll |v_r|$. Thus, the hydrodynamic variables can be solved as functions of r and t (cf. Figure 4a, b), with transient "pulses" representing the CIR inhomogeneity. The time coordinate then can be mapped directly onto a strictly co-rotating azimuthal angle (ϕ) coordinate, using the spiral streamline condition

$$\phi(r,t) = \int_{r_0}^{r} \frac{v_\phi(r')}{r' v_r(r')} dr' \; - \; \Omega t \ , \tag{9}$$

where Ω is the solar angular velocity in the ecliptic, and the streamline is assumed to begin at $r = r_0$, $t = 0$, and $\phi = 0$. Although the term dependent on v_ϕ is included for completeness, the approximation $v_\phi \rightarrow 0$ (in the inertial frame) is often justifiably taken far enough away from the solar surface. Figure 4c shows the resulting CIR stream structure computed by Hundhausen (1973) in this limit, and Figure 4d compares this data to that observed by the Vela 3 probe. Note that both forward and reverse shocks form at the leading and trailing edges of the compression just exterior to 1 AU.

More detailed numerical models of the non-linear hydrodynamic evolution of CIR's have been created, both in and out of the ecliptic plane. The fully three-dimensional MHD models of Pizzo (1978, 1980, 1982) show general agreement in the ecliptic plane with some previous two-dimensional models, but if the initial stream geometry is either inclined to the ecliptic or contains significant substructure, three-dimensional effects tend to produce significant non-radial motions which spread the compression over a larger and larger volume (cf. Siscoe 1976 for predictions of this in the outer solar system). Pizzo (1991) finds that magnetic torques should have a strong impact on the dynamics of three-dimensional MHD streams resulting from a coronal tilted dipole configuration. Inside ~ 0.5 AU, conditions resembling observed tangential discontinuities are reproduced via magnetic stress on

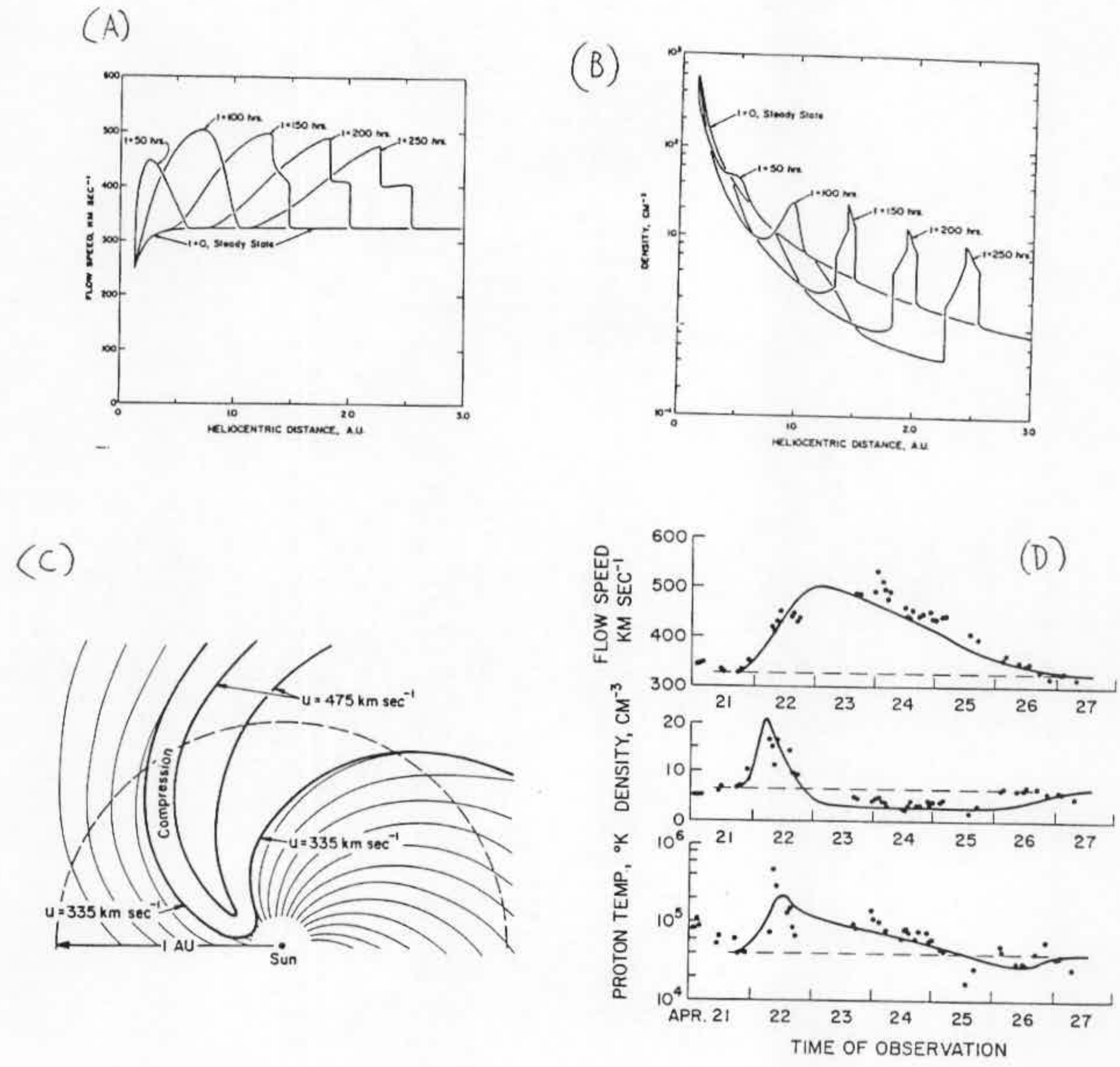

Fig. 4.— (A) Radial flow speed versus heliocentric distance for various times in Hundhausen's (1973) one-dimensional non-linear model. (B) Number density versus heliocentric distance for the same model. (C) The resulting time-steady co-rotating CIR structure from the same model. The light streamlines are that of the ambient flow, and the dark contours at $v_r = 325$ and 475 km/s indicate the extremities and peak of the high-speed stream. (D) Comparison of the radial velocity, number density, and proton temperature of the model predictions at 1 AU with the variations observed by Vela 3 in an actual high-speed stream.

"shear surfaces," and these geometric details in the outer corona directly impact upon the structure of the resulting CIR streams.

In the outer heliosphere ($> 5-10$ AU), other dynamical phenomena begin to take over. Because of the ever-increasing impact of pressure forces, the CIR streams widen in spatial extent, and can interact with one another. Two general types of interactions, (i) entrainment, and (ii) twin-stream interaction, are identified by Burlaga (1984). Entrainment results when one stream with a greater velocity amplitude overtakes one of lesser velocity (see Figure 5). If, however, the two streams have approximately equal velocities, these "twin" streams will still eventually interact when pressure forces result in their overall widening. Gosling, Hundhausen, and Bame (1976) discuss the spatial "filtering" of CIR's in the outer solar system, wherein small-amplitude streams quickly dissipate their energy (at small heliocentric distances) due to close-paired shock interaction, while larger streams tend to survive for longer times and distances. In all these processes, MHD turbulence should be an important factor, and there is still much theoretical research to be done.

4. Conclusions

Because the CIR phenomenon is basically produced by non-isotropic inhomogeneities in the dynamical variables (pressure, density, magnetic field) of the solar atmosphere and interior, there is no reason to believe that such structures are unique to solar type stars. Mullan (1984a, b; 1986) discusses the consequences of CIR-type features in both hot stars and cool giants and supergiants. Such observational signatures as discrete absorption components in ultraviolet P Cygni lines, "extended chromospheres" in cool supergiants, and discrepant asymmetries in the emission cores of Ca and Mg in K-type giants, all seem to suggest the existence of high-speed co-rotating streams in these stars. Recently, Henrichs (1994) has developed further justification for CIR's in early-type stars, based on magnetic field constraints and observations of rotationally-modulated discrete absorption components in such stars (cf. Prinja 1992).

The seemingly ubiquitous nature of the co-rotating high-speed stream in stars with winds, combined with the many interesting questions of three-dimensional MHD which arise, definitely makes this phenomenon merit further study. Not only does the existence of such structures allow us to probe the particles and fields surrounding the sun and many other stars, but they also provide detailed laboratories of radiation magnetohydrodynamics in, e.g., hot stars, where the presence of photons strongly affects the overall stellar wind. Thus, by observing and theoretically modeling CIR's in stars of many types, we can come to a much better understanding of their atmospheres, winds, and circumstellar environments.

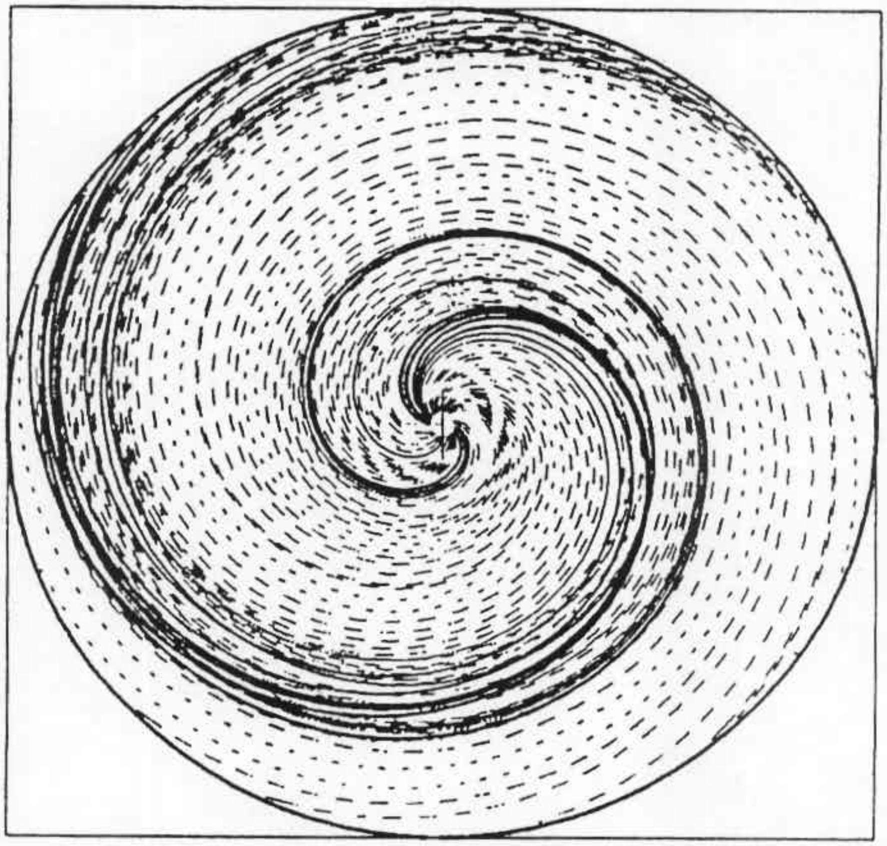

Fig. 5.— Magnetic field streamlines between 1 and 10 AU, based on a kinematic mapping of Voyager 1 observations near 2 AU. Heavy lines indicate strong fields, and dashed lines weak fields. Two CIR's, initially 180° apart, tend to coalesce at large distances due to entrainment (Burlaga 1984).

REFERENCES

Belcher, J. W. and Davis, L., Jr. 1971, *J. Geophys. Res.*, **79**, 3534.

Burlaga, L. F. 1984, *Space Sci. Rev.*, **39**, 255.

Burlaga, L. F. and Ness, N. F. 1969, *Solar Phys.*, **9**, 467.

Cally, P. S. 1987, *Solar Phys.*, **108**, 183.

Carovillano, R. L. and Siscoe, G. L. 1969, *Solar Phys.*, **8**, 401.

Davila, J. M. 1985, *Ap. J.*, **291**, 328.

Goldstein, B. E. 1971, *Rep. CSR-P-71-63* (Cambridge: Mass. Inst. Technol.).

Gosling, J. T, Hundhausen, A. J., and Bame, S. J. 1976, *J. Geophys. Res.*, **81**, 2111.

Henrichs, H. 1994, in *Pulsation, Rotation, and Mass Loss in Early-Type Stars*, IAU Symposium 162 (Dordrecht: Kluwer), in press.

Hundhausen, A. J. 1972, *Coronal Expansion and Solar Wind* (Berlin: Springer-Verlag).

Hundhausen, A. J. 1973, *J. Geophys. Res.*, **78**, 1528.

Hundhausen, A. J. 1977, in Zirker, ed., *Coronal Holes and High-Speed Wind Streams* (Boulder: Colorado Assoc. Univ. Press), 225-329.

Hundhausen, A. J., Bame, S. J., and Montgomery, M. D. 1970, *J. Geophys. Res.*, **75**, 4631.

Iucci, N., Parisi, M., Storini, M., and Villoresi, G. 1980, in Dryer and Tandberg-Hanssen, eds., *Solar and Interplanetary Dynamics* (Dordrecht: D. Reidel), 399.

Jackson, J. D. 1975, *Classical Electrodynamics* (New York: Wiley).

Kopp, R. A. and Holzer, T. E. 1976, *Solar Phys.*, **49**, 43.

Krieger, A. S., Timothy, A. F., and Roelof, E. C. 1973, *Solar Phys.*, **29**, 505.

Leer, E., Holzer, T. E., and Flå, T. 1982, *Space Sci. Rev.*, **33**, 161.

Levine, R. H. 1978, *J. Geophys. Res.*, **83**, 4193.

Mullan, D. J. 1984a, *Ap. J.*, **283**, 303.

Mullan, D. J. 1984b, *Ap. J.*, **284**, 769.

Mullan, D. J. 1986, *Astron. Astrophys.*, **165**, 157.

Ness, N. F., Hundhausen, A. J., and Bame, S. J. 1971, *J. Geophys. Res.*, **76**, 6643.

Neugebauer, M. and Snyder, C. W. 1966, *J. Geophys. Res.*, **71**, 4469.

Neugebauer, M. and Snyder, C. W. 1967, *J. Geophys. Res.*, **72**, 1823.

Parker, E. N. 1958, *Ap. J.*, **128**, 664.

Parker, E. N. 1963, *Interplanetary Dynamical Processes* (New York: Interscience Publishers).

Pizzo, V. 1978, *J. Geophys. Res.*, **83**, 5563.

Pizzo, V. 1980, *J. Geophys. Res.*, **85**, 727.

Pizzo, V. 1982, *J. Geophys. Res.*, **87**, 4374.

Pizzo, V. 1991, *J. Geophys. Res.*, **96**, 5405.

Pneuman, G. W. 1986, *Space Sci. Rev.*, **43**, 105.

Pneuman, G. W. and Kopp, R. A. 1971, *Solar Phys.*, **18**, 258.

Prinja, R. K. 1992, in Drissen et al., eds., *Nonisotropic and Variable Outflows from Stars*, A.S.P. Conference Series, **22**, 167.

Sakurai, T. 1985, *Astron. Astrophys.*, **152**, 121.

Schlüter, A. 1957, in van de Hulst, ed., *Radio Astronomy* (IAU Symposium Proceedings), **4**, 356.

Schwenn, R., Montgomery, M. D., Rosenbauer, H., Miggenrieder, H., Mulhauser, K. H., Bame, S. J., Feldman, W. C., and Hansen, R. T. 1978, *J. Geophys. Res.*, **83**, 1011.

Siscoe, G. L. 1976, *J. Geophys. Res.*, **81**, 6235.

Siscoe, G. L. and Finley, L. T. 1972, *J. Geophys. Res.*, **77**, 35.

Siscoe, G. L., Turner, J. M, and Lazarus, A. J. 1969, *Solar Phys.*, **3**, 456.

Smith, E. J. and Wolfe, J. H. 1977, in Shea et al., eds., *Study of Traveling Interplanetary Phenomena* (Dordrecht: D. Reidel), 277.

Snyder, C. W. and Neugebauer, M. 1964, *Space Res.*, **4**, 89.

Suess, S. T. 1979, *Space Sci. Rev.*, **23**, 159.

Venkatesan, D., Shukla, A. K., and Agrawal, S. P. 1982, *Solar Phys.*, **81**, 375.

Whang, Y. C. and Burlaga, L. F. 1986, *J. Geophys. Res.*, **91**, 13341.

Wilcox, J. M. and Ness, N. F. 1965, *J. Geophys. Res.*, **70**, 5793.

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