THE INFLUENCE OF THE ANOMALOUS COSMIC-RAY COMPONENT ON THE DYNAMICS OF THE SOLAR WIND

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Abstract. It is well known that both the galactic and anomalous cosmic rays show positive intensity gradients in the outer heliosphere which are connected with corresponding pressure gradients. Due to an efficient dynamical coupling between the solar wind plasma and these highly energetic media by means of convected MHD turbulences, there exists a mutual interaction between these media. As one consequence of this scenario the enforced pressure gradients influence the distant solar wind expansion. Here we concentrate in our theoretical study on the interaction of the solar wind only with the anomalous cosmic-ray component. We use the standard two-fluid model in which the cosmic-ray fluid modifies the solar wind flow via the cosmic-ray pressure gradient. Then we derive numerical solutions in the following steps: first we calculate an aspherical pressure distribution for the anomalous cosmic rays, describing their diffusion in an unperturbed radial solar wind. Second, we then consider the perturbation of the solar wind flow due to these induced anomalous cosmic-ray pressure gradients. Within this context we especially take account of the action of a non-spherical geometry of the heliospheric shock which may lead to pronounced upwind-downwind asymmetries in the pressures and thereby in the resulting solar wind flows. As we can show in our model, which fits the available observational data, radial decelerations of the distant solar wind by between 5 to 11% are to be expected, however, the deviations of the bulk solar wind flow from the radial directions are only slightly pronounced.

1. Introduction

The discovery of the anomalous cosmic-ray (ACR) component more than fifteen years ago (Garcia-Munoz, Mason, and Simpson, 1973) has made available a new instrument to explore the global physical scenario of the interaction of the solar wind with the Local InterStellar Medium (LISM) and thereby to study the composition of the LISM and the physics of the cosmic-ray acceleration mechanisms. Nowadays, it is generally accepted that the enhancements in the energy spectra of cosmic-ray species like H, He, N, O, Ne, Ar, and C in the range of 20–100 MeV nucl−1 are due to a conversion of originally interstellar particles into energetic singly-ionized ion species near the termination shock of the solar wind. The detailed scenario here is the following: neutral particles of the LISM penetrate into the heliosphere and become ionized by charge exchange collisions or photo-ionization. This enables their pick-up by the solar wind magnetic fields, which converts them into a suprathermal ion constituent and convects them in the antisolar direction towards the LISM. Fisk, Kozlovsky, and Ramaty (1974) have suggested that these suprathermal ions may be accelerated by MHD turbulence.
connected with interplanetary shock waves (Fisk, Kozlovsky, and Ramaty, 1974) or by plasma waves in general (see also Klecker, 1977), both connected with the so-called corotating interaction regions (CIR's) (see Pizzo, 1982, 1986, for an overview). These mechanisms would lead to a source region for ACR-particles located with its maximum at a heliocentric distance of about 10 AU. However, recent measurements of a positive radial gradient of the anomalous cosmic ray intensity up to heliospheric distances of 50 AU (Cummings and Stone, 1988; Webber, 1989) have ruled out this mechanism as the dominant acceleration scenario. The main source of the ACR must be located somewhere ahead of the present position (i.e., at $R > 45$ AU) of the deep space probes VOYAGER 1, 2 and PIONEER 10, 11, that permanently increase the region of the explored heliosphere during their approach to the outer boundary of the solar system. Thus, the most probable cause for the acceleration of the suprathermal particles as it appears now is the solar wind termination shock (as was pointed out by Pesses, Jokipii, and Eichler (1981) for the first time). A small fraction of the picked-up interstellar ions that are convected outwards with the solar wind is transformed there to a cosmic-ray component by the first-order Fermi acceleration mechanism (Jokipii, 1986, 1990). These particles, if energized enough so that their spatial diffusion rates become large again, penetrate into the inner parts of the heliosphere where they are observed as the ACR component.

From this complicated chain of consecutive processes, the importance of an understanding of the origin of the ACR becomes evident. If the outlined theory is correct, (i) the existence of the ACR is a strong argument favouring the existence of a heliospheric shock at a distance of 80–100 AU (Jokipii, 1990) and therefore supports the general scenario of the interaction of the solar wind and the LISM, which naturally involves such a shock transition of the solar wind flow. (ii) The elemental composition of the ACR, if based on well founded theoretical models, gives fairly direct information about the composition of the LISM, though this connection is not as straightforward as thought in the past (Fahr, 1990).

As a consequence of (i) Jokipii has already mentioned that the ACR component may modify the solar wind flow and the shock, if the heliocentric shock distance is significantly greater than 80–100 AU, because then the energy densities of the solar wind and the ACR component may be dynamically more important than the galactic cosmic rays (GCR) due to its smaller diffusion coefficient and, as a result, its better coupling to the gas flow. As we will show here, even an ACR source located at 79 AU, i.e., the lower limit of the derived probable shock distance in the upwind direction, would have noticeable dynamical consequences for the distant solar wind expansion.

Another main point of our investigation in this paper is the upwind-downwind asymmetry of the pressure distribution of the ACR, which is a direct consequence of an upwind-downwind asymmetry of the termination shock. This fundamental asymmetry of the heliosphere (see the recent review by Fahr and Fichtner, 1991) was already attributed to the heliospheric shock by Dessler (1967). His somewhat intuitive and only qualitative considerations appear to be well confirmed by new detailed numerical calculations of a supersonic stellar wind interacting with the interstellar medium (Shima,