CONVECTIVE FLOWS AROUND SUNSPOT-LIKE OBJECTS

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Abstract. Results are given for calculations of convective flows around objects in the outer layers of the Sun that have similar characteristics to small sunspots. These objects are allowed to radiatively (diffusively) exchange heat with their surroundings, but convective motions and exchange are absent. This assumption is based on the simple presumption that a sunspot magnetic field maintains pressure equilibrium with the surrounding medium and prevents convective exchange with that medium.

The flow structure around the object, and the question of the overall balance or redistribution of the emerging heat flux as suggested by earlier empirical models, are studied and discussed.

After a period of adjustment, shortly after the sunspot-like object is placed into the domain, the layer readjusts itself so that most of the heat flux actually reappears at the surface, although some fraction of the flux is carried horizontally far from the object. There is no indication of long term storage of the heat flux that would normally appear in the place where the object resides. Finally, when the object is removed, the surrounding medium responds very quickly and soon returns to the undisturbed state before the object was in place.

The present numerical treatment includes restrictions that may influence aspects of the heat redistribution, convective flows and time scales. In particular, the shape of the object and its size (somewhat smaller than a sunspot) are important, as is the number of spatial dimensions and the treatment of some boundary conditions. Since all of these issues require further investigation, some discussion is presented regarding the applicability of our results to real sunspots.

1. Introduction

Upon analyzing the first few months of data from the ACRIM experiment on SMM, it became clear that the total solar irradiance decreased when a sunspot area crossed the solar limb, reaching a minimum when the area crossed the central meridian (Willson, Hudson, and Chapman, 1981). It was in fact possible to explain the irradiance depression from the size of the projected sunspot area and the contrast between photospheric intensity and spot intensity as a function of location on the solar disk. Oster, Schatten, and Sofia (1982) were able to explain the entire variability of the total irradiance by adding the positive contribution of faculae according to intensity contrasts with the photosphere (as a function of distance from disk center) measured by Frazier (1971) and Chapman (1980). Since facular areas are not routinely available on a daily basis, they assumed that facular areas were approximately equal to the readily available areas and locations of Ca II plages. This scheme was used by Sofia, Oster, and Schatten (1982) to successfully simulate what the ACRIM experiment should have measured for the rest of 1981 when the data analysis was completed. They concluded that within

an error margin of approximately $10\%$, the average depression of the spot deficit was offset by the average facular excess. Because faculae last longer than sunspots, the spot depression during a typical solar rotation dominates over the facular excess during that rotation, so that an energy storage is suggested. On the other hand, because of the average behavior on the longer time scale, the storage should not exceed the lifetime of the faculae, which is of the order of one month.

Subsequent models of the total irradiance involving longer observation times (Schatten et al., 1985) showed that because of large uncertainties in the observed values of sunspots and facular sizes, the balance between the energy deficit due to sunspots and the energy excess due to faculae within the $10\%$ limit obtained in the first modelling exercise was fortuitous, and that in fact the balance was within approximately $50\%$. On the other hand, competing empirical models concluded that the facular contribution was no larger than $10\%$ of the sunspot depression, so that much longer term storage was indicated (cf. Hoyt and Eddy, 1982). To investigate this discrepancy it is useful to model the energy and material flow around a sunspot to see what happens to the blocked energy.

The magnetic field in a sunspot impedes convective energy transport and leads to the reduced specific intensity emerging through the sunspot (Biermann, 1941). This causes an entropy increase below the sunspot region which sets up an enhanced energy flux and material motions around the spot in an attempt to re-establish quasi-hydrostatic and thermal equilibrium between the disturbed region and its surroundings.

To treat this problem in a realistic way it is necessary to know the detailed configuration of the spot and faculae magnetic fields below the photosphere since it appears that the interaction between the flow and the magnetic field affects the surface structure of the active region producing a 'depression' (Spruit, 1976; Zwaan, 1978) or a 'hillock' (Schatten et al., 1986). These two descriptions were postulated to account for the directionality of the facular contrast. Since information does not currently exist to accomplish this, it is hoped that an approximation assuming simple spot geometry and no surface geometric effects, e.g., as done by Spruit (1977), will provide useful results.

The earliest models of this type were carried out by Spruit (1977) where time-dependence of the problem as well as systematic flows were neglected, and by Foukal, Fowler, and Livshits (1983) and Chiang and Foukal (1984), where time-dependence was considered, but still no flows were allowed. The results of these investigations indicated that, because of the much stronger thermal contact between the perturbed region and the deep convection zone than between the perturbed region and the surface, the large majority of the sunspot-blocked energy would be diffused into the entire solar convective region to be released on a thermal time scale of this region (i.e., about $10^3$ years). More recently, Nye, Bruning, and LaBonte (1988) considered this same problem, but included both energy and mass flow in the linear approximation. They found that significant mass flows were generated by the thermal energy blocked by the spot, but that these flows were not accurately in agreement with observations. In this paper we will consider almost the same problem, but in the fully nonlinear compressible regime. In particular, we wish to ascertain the flow around a sunspot-like object at various depths in the solar