Long term variability of heliopause due to changing conditions in local interstellar medium

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Abstract. Recent studies have shown that local environment of the Sun is a complex one with the presence of several supernova shock bubbles and interstellar clouds in the local interstellar medium (LISM). Even within this environment, the Sun is moving with a velocity of about 15 km/s toward the interior of the galaxy. We examine the changes in the local ISM environment experienced by the Sun in the past and then discuss interaction of the Sun with these different environments. Lastly, we enquire how this may have changed the cosmic ray environment of the Earth and highlight how this method can be applied to test the changes in the local ISM environment over astronomical time scales.

Index Terms. Heliosphere, cosmic ray modulation, long term variability.

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1. Introduction

Recent studies of the local interstellar medium (LISM) reveal that the Sun is in a complex environment where at least three and perhaps more bubbles or cavities of probable supernova origin are interacting (see e.g. Breitschwerdt, 2001; Frisch, 1995, 1998; Maiz-Apellaniz, 2001; Smith and Cox, 2001 and references therein).

Reviews by Frisch (1995, 1998) have mapped the local interstellar matter (LISM) from several observations based on back scattering and extinction of soft X-rays coming from nearby sources. These maps show that the local interstellar medium is largely governed by a collection of at least three large bubbles or super bubbles that seem to be shells of supernova remnants of age between 5 and 10 million years. A large region in which the Sun seems to be sitting is referred to as local bubble. These observations have been re-enforced by radio observations of more recent studies based on the measurements of the turbulence in the nearby pulsar radio emission due to the LISM plasma (Ramesh Bhat, Gupta and Pramesh Rao, 2001). They have modeled the inferred plasma distribution into a 3 component model that gives a description of the LISM derived from X-ray observations.

Redfield and Linsky (2002) have attempted to study the UV observations of FeII, MgII and CaII to determine the structure of the LISM up to 100 pc. They have shown that combined studies of absorption features and Doppler shifts indicate a fairly inhomogenous distribution of the LISM. Further high resolution studies in ultraviolet (Shelton, 2002) and infrared bands (Franco, 2002) from select regions show that there is evidence of hot but quiescent plasma in the LISM. A more detailed compilation of the H_α lines in the Milky Way by Haffner (2002) has shown that conditions of the warm interstellar medium and diffuse ionised gas suggest a rich mix of filamentary structures in the ISM. Similarly, first results from the FUSE mission (Moos et al., 2002) suggest that UV emission in the the warm component of the local bubble is homogeneous characteristic of an old bubble.

Some of these shells seem to be disintegrating and forming fluffy clouds that are drifting within these shells or loops (see also Ricardo and Beckman, 2001; Seth and Linsky, 2001; Smoker et al., 2002). Meisel, Diego and Mathews (2002) have calculated the detailed trajectories of several dust grains approaching the Sun and shown that they are indeed of interstellar origin. The dust content of the bubble has been estimated from the Ulysses by Ingrid and Hirshi (2002).

These observations are in good agreement with models of the ISM that involve several shells in dynamic equilibrium between slowly dying supernova remnants of age of the order of a few million years (e.g. Smith and Cox, 2001) which are disintegrating into small clouds.

Donato, Manrin and Taillet (2002) have attempted to model the confinement of cosmic rays in these bubbles and the production of radio active nucleids in spallation inside the local bubble. They have shown that production rates of some radioactive nuclei such as ^{10}Be, ^{28}Al and ^{36}Cl can be important markers of the spallation rates in the LISM.

It is therefore clear that we have a fairly consistent broad picture of the local interstellar medium (see Fig. 5, Frisch, 1995). Another interesting feature is that the Sun itself is not at rest in the local rest frame (Frisch, 1995, 1998) and has a proper motion of about 15 km/s toward the inner part of the Galaxy. Dehnen and Binney (1998) have given a more detailed value of the movement vector of the Sun in the local

ISM using the Hipparcos data. They show that the best fit vector for the Sun is u_0=10.00 ± 0.36 km/s, v_0 =5.25 ± 0.62 km/s in the plane of the Galaxy and w_0 =7.17 ± 0.38 km/s perpendicular to the plane of the Galaxy towards the galactic plane. However, this motion in the perpendicular plane is believed to be cyclic with a period of 66 million years (see also Frisch, 1998). The result is that the Sun has been encountering a large range of ISM conditions during the voyage of the Sun over the last few million years. While attempts have been made to model the dynamics of the ISM no studies have been undertaken to understand the interaction of the Sun under these varying conditions. In the next section we consider the changing environment seen by the Sun over the last few million years. In section 3 we consider various processes by which the Sun interacts with the local interstellar medium and in section 4 we concentrate on the modulation of the average galactic cosmic ray fluxes due to these differing environments and show that the observed cosmic ray fluxes on earth would vary significantly due to different ambient LISM conditions.

2. Position and relative movement of the Sun

We begin backtracking the path of the sun based on our current understanding of the velocity of the sun in LISM and the LISM environment. For this we refer to Fig. 5 of Frisch (1995). The sun is moving in the LISM toward the region of Galactic coordinates of (l,β) = (51° , 23°)with a speed of 15.4 km/s (Frisch, 1995)with respect to the local rest frame. The Scorpius-Centaurus association is a large number of massive stars. Several supernova explosions have occurred in this region over the last 15 million years. It is generally believed that the Sun is inside the supernova bubble created by supernova remnants from this region. Smith and Cox (2001) consider the option that the local environment is a result of two or three supernovae that went off in the region occupied by the Local Bubble that itself could have originated from the Scorpius Centaurus Association. The center of the Gould belt of young stars is located at a mean galactic longitude of 110° with a diameter of 200 pc (Poppel, 1997). The Taurus and Perseus region lies in the anti galactic center region while the Orion loop lies in the Galactic Longitude of l about 200°.

We trace the motion of the sun *back* from this location. This is in line with the inferences of Bash (1986) who calculated the approximate path of the Sun over a long period. The details of the movement are in table 1. The first column of the table gives the epoch before present when the Sun was in the neighborhood of a particular region and the duration for which it was in a specific neighborhood. It should be noted that there is a broad range of period when the Sun was in the inter arm region passing by the Geminga Pulsar region and it was *inside* the Orion Nebula about 25 million years ago for about half a million years. It may be noted that the linear interpolation of the Fig. 5 of Frisch (1995) would indicate the Sun missing the Orion arm but the arm itself has a motion orthogonal to the solar direction with a velocity of about 1 km/s (Nagahama et al., 1998). It seems more than a coincidence that it is during this period, when the local ISM was clearly more dense that the Earth seems to have encountered larger mass extinction periods. Since high density LISM and interplanetary environment would increase friction and decay the comet trajectories quite considerably. However, we do not discuss this issue here.

By extrapolation, we see that the sun passed from the Persius arm through the inter-arm region into the Orion belt. The sun escaped the supernova and entered the fluff in which it presently placed. The higher densities of diffuse gas seen within 50 pc of the sun between galactic longitudes 20° and 90° represent diffuse gas ablated from the parent molecular cloud complex. In the next section we discuss the physical processes through which the sun must interact with these regions before discussing the astronomical consequences.

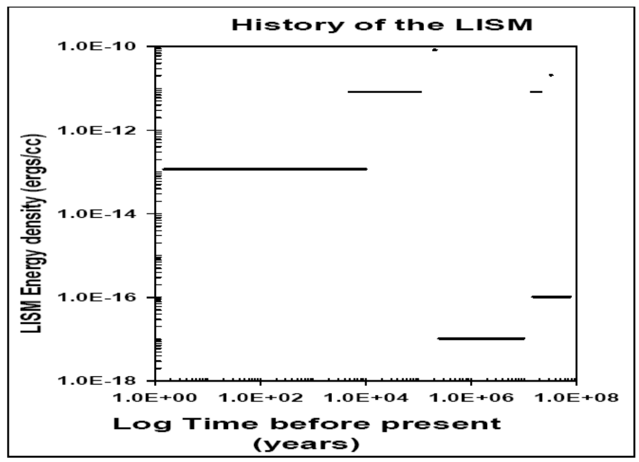

Fig. 1. Mean LISM energy density over the last 10 million years.

In Fig. 1 we have plotted the energy density of the local ISM as a function of time. On the X-axis is the time in log scale and on Y-axis we have plotted 1.5 kT_{ISM} ρ_{ISM}, where T_{ISM} is the ISM temperature and ρ_{ISM} is the ISM density and k is the Boltzmann's constant (Table 1 (see also Vahia and Lal, 2000)). As can be seen from the figure, ISM densities have seen large changes in energy density over the last hundred million years for which data is given here.

3. Physical processes of interaction of Sun with the LISM

There are mainly three processes through which the interstellar gas is affected by stars (Dyson and Williams, 1997). A graphical description of these processes is given in Fig. 2.

A massive hot star will photoionize the interstellar gas in its neighborhood and photons of energy $h\upsilon \sim I_H$ (where ($I_H$is the ionization potential of hydrogen) will eject electrons from the atoms. The energy excess, $h\upsilon - I_H$, goes directly into

Table 1. Solar Movement in the ISM

Time (yBP) (a)		dT (y)	Region	Density (cm^{-3}) (Temp (K))	Comments (b)
Start	End				
0	1.0 10^4	1.0 10^4	Fluff	0.08(7000)	Size 5 pc, From SCA moving in orthogonal direction to Sun 20 km/s B = 1.5 μG. Highly Inhomogeneous (1)
1.0 10^5 (a)	3.1 10^5	6.0 10^3	SN (?)	4 (10^4)	Geminga? (2,3)
1.0 10^4	1.0 10^5	0.1 – 1 10^5	Bubble	0.04 (10^6)	Expanding bubble from SCA. Age 15 My, vel ~ 4 10^4 km s^{-1} orthogonal to Sun. B ~ 1.5 μG
1.0 10^5	1.0 10^7	(.01 – 1) 10^7	Inter –arm	0.0005 (100)	(1,6)
1.0 10^7	2.5 10^7	3.0 10^6	HI shock	4 (10^4)	From Gould belt (7). Duration is taken as that for earlier SN (3,6)
2.5 10^7 (a)	4.0 10^7	5.0 10^5	Orion Belt	10^4 (10)	Size 5 pc, Sun must have taken 5 10^5 yrs to cross at current velocity (7,8)
4.0 10^7	5.0 10^7	(2.5 – 4) 10^7	Inter - arm	0.005 (10)	(6)
5.0 10^7	6.0 10^7	(4-5) 10^7	Persius Arm	1 (1000)	Duration uncertain (6)
$\leq 10^7$					(9)

(a) For SN the start and end time are the interval between which the SN spike crossed the earth, (b) Bracket numbers in comments refer to notes.

References: 1. Frisch (1995); 2. Ramadurai (1993); 3. Sabalska et al. (1991); 4. Egger et al. (1996); 5. Van der Walt and Wolfendale (1988); 6. Bash (1987); 7. Clube and Nupier (1984).

Notes to the table:

1) SCA refers to Scorpius Centaurus association at l = ~ 300-360°. About 35 SNR have been identified in this region (Whiteoak and Green, 1996).
2) While Frisch (1995) claims that the evidence for Geminga is not there, Ramadurai(1993) has claimed the passage of a SN shock around 30,000 yrs ago that arose from a source around the age of Geminga. The sun crossed the vicinity of the parent star of Geminga 10^7 yrs BP while the SN itself is 3 10^5 yrs old (Pavlov, 1997). The temperature and density are typical values for SNR (Harwit, 1998). The shock passage is calculated assuming a shock front velocity of 1000 km/s (1 pc/My) and taking an effective thickness of 1 pc (Harwit, 1998). These parameters are similar to those derived by Szabelska, Szabelski and Wolfendale (1991). Based on ^{10}Be data they argue for the passage of a supernova shock front near the Sun about 30,000 yrs ago.
3) Another SN is just arriving from the SCA association, age ~ 11 My.
4) The bubble is from the SN shell from the Upper Centaurus Lupus of SCO. Age ~ 14-15 My BP.
5) The inter-arm region is derived from Fig. 5 of Bertrische (1998) and Bash (1987), Fig. 1.
6) van der Walt and Wolfendale (1998) argue that the gamma ray data suggest that the inter arm cosmic ray are of lower intensity and have a steeper spectrum.
7) More than 130 weak line T Tauri (O type) stars have recently been cataloged in this region (for reference see Wichmann et al., 1997)
8) Based on extrapolation as defined in note 5.
9)
9 A)We are now in the Orion structure in the inter arm region between Persius and Carina arms
9 B) This is uncertain since collisions with individual objects are ignored (Bash, 1987). Clube and Napier, (1984) suggest that in the last 4.5 10^9 years, the sun has encountered about 10 molecular clouds. Napier (1985) has done a more detailed analysis to show that the Sun has had near collisions (impact parameter < 20 pc) with 56 GMCs having > 3 10^3 M_{sun} and 8.2 close encounters with GMCs having M > 10^5 M_{sun}
9 C) Our galaxy is a highly evolved spiral with about 10% of its mass in diffuse gas; the rest is in stars. The sun is located slightly above the galactic plane, and is moving through space at 16.5 km/s with respect to the local standard of rest. The Sun oscillates in the galactic plane with a period of 33 My (i.e. it goes ± 56 pc).
9.D) Taking the Sun's relative velocity of 16.5 km s^{-1} (2 pc/My), in the local rest frame, the sun has traveled 9 kpc in 4.5 billion years. Taking the solar distance as 8 kpc from the center, this gives a radius of ~ 50 kpc. The sun therefore has travelled only about 18 percent of the distance in the local rest frame. In the galactic frame, the solar velocity is 250 km/s and hence the Sun has completed about 23 rotations in its life time.

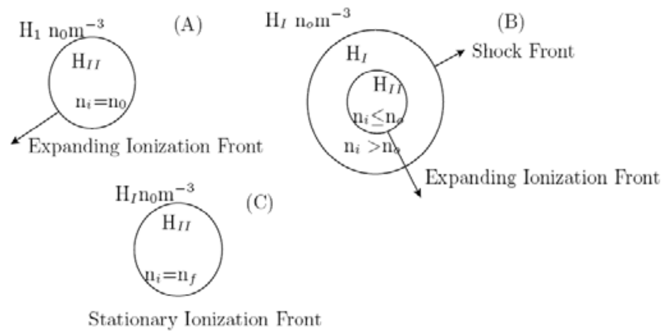

Fig. 2. Evolution of the interaction region between the Sun and the LISM.

kinetic energy of the detached electron. The protons are essentially unaffected by this process although momentum conservation demands that they experience a small recoil. The strong Coulomb interaction between protons and electrons produces the inverse process of recombination. The reversible reaction can be stated as $H + h\upsilon \leftrightarrow p + e^-$. The energy of the photon produced on recombination is given by the sum of two contributions: the kinetic energy of the recombining electron and the binding energy of electron in the energy level into which it recombines. This binding energy is equal to I_H/n^2, where n is the principal quantum number of the level into which recombination occurs. This is called the Stromgren Sphere and its size is called Stromgren radius (SR).

Due to photoionization, the gas temperature increases from about 10^2 K to about 10^4 K. The ionization process itself increases the number of gas particles and therefore the pressure by a further factor of two. The pressure in the ionized gas is thus two hundred times greater than that in surrounding neutral material. This ionized gas expands and a shock front is set into motion. The result is the formation of an outer sphere whose inside edge is defined by the ionization radius and outer radius defined by pressure equilibrium with the local interstellar medium. This is called the Photo Ionization (Ph) Front.

The other methods of interaction are via the solar wind (very high-speed continuous mass loss) which produces a mechanical piston that is bound by pressure equilibrium between the solar wind (SW) and ISM and its edge is called the Heliopause (HP).

While all three processes occur simultaneously in the interaction of the Sun with the interstellar medium, in the present study we study each process independently based on the formulation of Dyson and Williams (1997). See Vahia (2004) for more details.

The three interacting regions can be separately solved and the relation between the various parameters can be given as follows (Vahia, 2004).

$$R_s = (0.75\,\pi\, S_{sun}/n^2\, \beta_2)^{1/3} \quad (1)$$

$$R_{Ph} = R_s\,(1+1.75\, V_{sound}\, t/R_s)^{4/7} \quad (2)$$

$$R_{SW} = (n_{SW}\, T_{SW}/n_{ISM}\, T_{ISM})^{3/4}\, R_{Sun} \quad (3)$$

where R_s is the Stromgren Radius, R_{Ph} is the radius of the photo-ionisation front and R_{SW} is the radius of the shell produced by the solar wind. S_{Sun} is the solar UV flux, R_{Sun} is the radius of the Sun, V_{sound} is the velocity of sound in ISM, t is the time and n and T are the number density and temperature of appropriate regions.

In Table 2, we have given the numerical values of various physical parameters.

Table 2.

Parameter	Fluff	Fluff2	Bubble	Inter arm	GMC	Arm
n (p/m^3)	8.0 10^4	1.6 10^7	4.0 10^4	5.0 10^2	1.0 10^{10}	1.0 10^4
T_e (Kelvin)	7.0 10^3	1.0 10^3	1.0 10^6	1.0 10^2	1.0 10^1	1.0 10^3
Time (seconds)	1.0 10^2	1.0 10^2	1.0 10^5	1.0 10^7	1.0 10^8	1.0$10^9$
Recomb coeff. β_2 (m^3/s)	2.61 10^{-19}	1.12 10^{-18}	6.32 10^{-21}	6.32 10^{-18}	3.56 10^{-17}	1.12$10^{-18}$
Recom Fact α	6.22 10^{-13}	1.64 10^{-12}	5.20 10^{-14}	5.20 10^{-12}	1.64 10^{-11}	1.64 10^{-12}
Recomb time t_R (seconds)	4.78 10^{13}	1.11 10^{13}	1.98 10^{15}	1.98 10^{12}	3.51 10^{11}	1.11 10^{13}
$Mism$ (Kg)	1.86 10^{21}	3.73 10^{23}	9.32 10^{20}	1.16 10^{19}	2.33 10^{26}	2.33 10^{20}
$V_{sound}(m/s)$	1.21 10^4	4.56 10^3	1.44 10^5	1.44 10^3	4.56 10^2	4.56 10^3

In Figs. 3 and 4 we have plotted the depth of the interaction regions under different ISM conditions and different physical processes. The fluff1 refers to the dynamically variable fluff while fluff2 refers to the fluff dimension under equilibrium conditions.

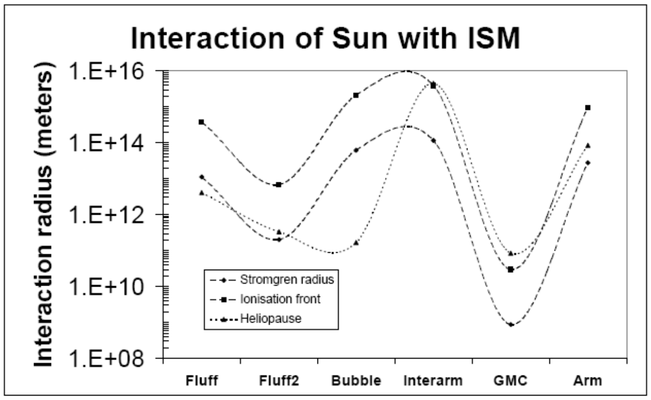

Fig. 3. Interaction redius of the Sun under different LISM conditions

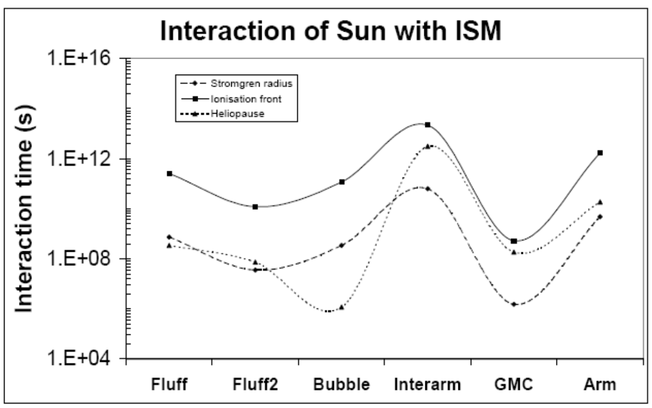

Fig. 4. Timescales of reaching equilibrium under different LISM conditions.

As can be seen from the Fig. 3, the SR is four orders of magnitude larger than the HP that is normally considered the boundary region of solar interaction with the interstellar medium. While SR decreased by two orders of magnitude as the Sun entered the Local Fluss, inside the Supernova, the HP remained more or less constant during the movement of the Sun from Bubble to the Fluff. This is because the HP depends on the density and temperature of the medium, while SR depends only on the ISM density. It should be noted that the variations in all the three radii can be of the order of 6 orders of magnitude. The time scaled to reach equilibrium are also varied (Fig. 4). As can be seen from the Fig., in he low density region of the bubble, the HP reached equilibrium in less than 1 year but it would take more than 100 years to reach the equilibrium in the fluff. On the other hand the local environment of the GMC, the SR and Ph would not reach equilibrium state for any realistic time scales.

Recently Malama et al. (2006) have done a detailed modeling of the heliospheric interface using multi-component nature of the heliospheric plasma. They show that their model agrees well with other similar model. However, for the present we use this simplified model since it allows us to estimate *relative* changes in the cosmic ray flux over long periods of time. Also, Alexashov and Izomodenov (2005) have studied the relative merits of kinetic and multifluid models and conclude that multi-fluid models are likely to give inaccurate results compared with kinematic models of the kind considered here.

4. Cosmic ray modulation

Cosmic rays are charged particles that come to us from the galaxy. The interaction region between the ISM and the Sun heavily modulates them. We assume that the generic interstellar spectrum of the cosmic rays is given by the function of the form

$$f(E) = C\,E^{-2.5} \quad (4)$$

where E is the kinetic energy of the cosmic rays. This spectral form is assumed based on very high energy ($\geq \sim 10^{14}$ eV) cosmic ray data. As we show below, these cosmic rays are not significantly modified by the various processes considered here.

Since these are charged particles, they are significantly affected by the potential difference produced due to the interactions discussed above. It has veen shown in Vahia (2004) (see e.g. Lockwood and Webber, 1995, Garcia Munoz, 1975; Garcia Munoz et al., 1990). The differential flux of cosmic rays at any energy E of cosmic rays is given by

$$J(E,f)=AE(E+2E_0)(E+\varphi+m)^{-\alpha}/(E+\varphi)(E+2E_0+\varphi) \quad (5)$$

where

$$m = B - Ce^{-(E/D)} \quad (6)$$

where *A, B, C, D* are constants and equal to 5×10^8, 1150, 650 and 1500 respectively. We obtain their values from the current best fits for cosmic ray spectra. E is the kinetic energy in MeV/n, E_0 is the rest mass energy, and α is the slope of the incident particles.

In Figs. 5, 6, and 7 we have plotted the cosmic ray modulation under different ISM conditions. In all the cases we have assumed that the cosmic rays have an initial spectrum index of -2.5 in energy impinge on the sphere. We calculate the potential generated by the each sphere and evaluate the flux parameters.

In Fig. 5 we show the effects of SR on the cosmic ray modulations. Since this shock front is generated due to ionization and since its radius is much larger, the modulation is also more dramatic. Fig. 6 shows the modulation produced by the IF which extends beyond SR and therefore also affects the CRs more severely. In Fig. 7, the variations due to the changes in the Heliopause alone are shown. As can be seen from the figure, in the low energy can be as much as 6 orders of magnitude due to the variation of the Hp alone. Note that a very high energy density in cosmic rays comes from the low energy anomalous cosmic rays, which are accelerated in the Hp itself. For the present study we have ignored this component. Also, Ferreira and Scherer (2004) have shown that while measuring cosmic rays *in situ* there will be a difference in the cosmic ray flux in the direction of motion of cosmic rays. However, since we are dealing with time averaged fluxes which are not sensitive to these effects in the present paper. Similarly, Combet et al. (2005) have calculated the affects of spallation on heavy element abundances but we do not consider those here.

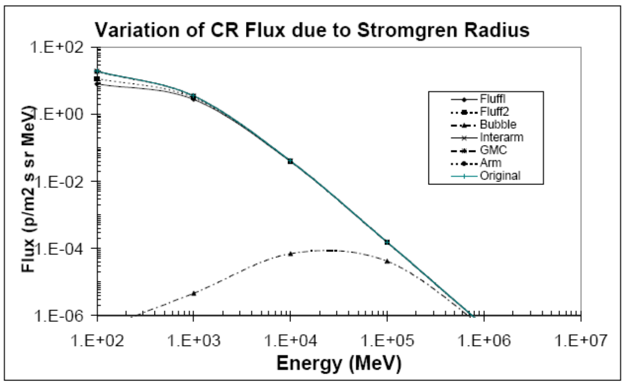

Fig. 5. Variation of cosmic ray flux due to stromgren radius.

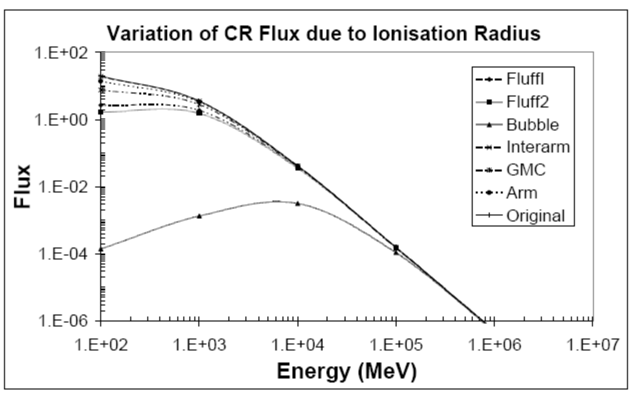

Fig. 6. Variation in cosmic ray flux due to ionisation front.

In Fig. 8 we have plotted the cosmic ray energy density over a period of time. The flux is calculated based on the assumption that the solar system is embedded in a specific environment as given by table 1 and that all the three forms of interactions discussed above are in equilibrium.

We plot the minimum flux that will pass through the three interaction regions and take that as the final flux that would be seen by the solar system. Note that the two phases of passage through a SN and an Hp front are not plotted since these are period of local and intense cosmic ray re-acceleration which have been ignored in the present work.

If the present analysis is borne out by further studies, this may be an important component in producing the knee in the cosmic ray spectra.

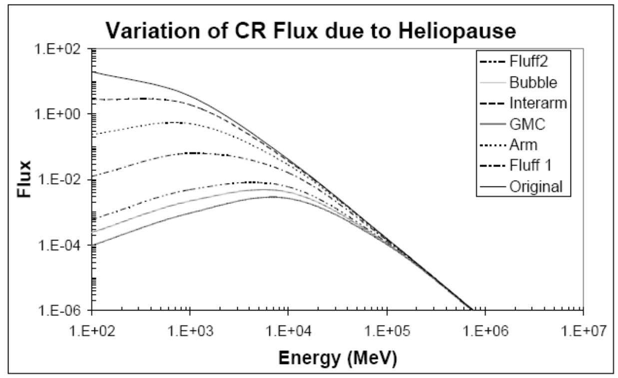

Fig. 7. Variation of cosmic ray flux due to the heliopause.

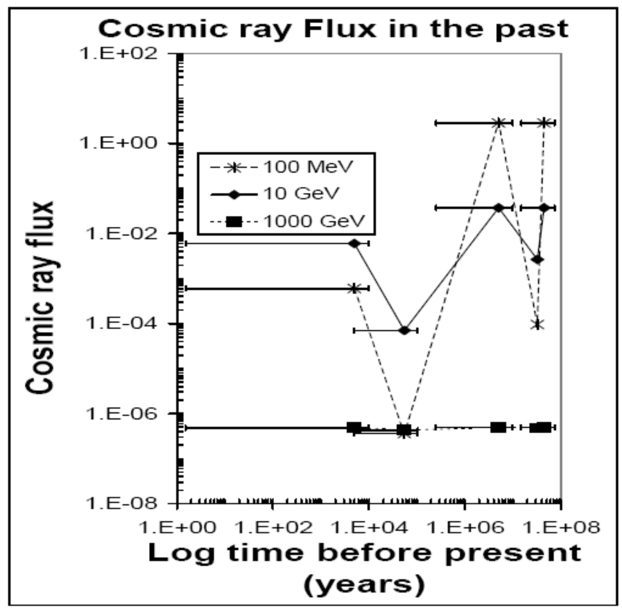

Fig. 8. Long term variations of cosmic ray flux.

5. Conclusions

We have investigated the interaction of the Sun with the local interstellar medium. We show that there have been dramatic changes in the LSIM condition in the last 40 million years or longer. We then investigate the physical processes through which the Sun interacts with the LISM and show how these regions of interaction would be dramatically different for varying ISM conditions. We investigate radiative modulation, radiation induced ionization front and the classical solar wind interaction of the ISM. We then investigate the affects of these interaction regions on the modulation of cosmic rays. We find that the first two parameters will have significant affect on cosmic ray modulation though this has generally been neglected in the literature.

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