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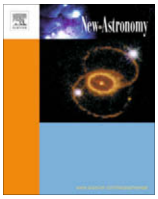

# Imprint of distortions in the Oort Cloud on the CMB anisotropies

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ABSTRACT

We study the effect of a close encounter of a passing star on the shape of the inner Oort Cloud, using the impulse approximation. The deviation of the perturbed Oort Cloud from sphericity adds angular fluctuations to the brightness of the cosmic microwave background (CMB) due to thermal emission by the comets. An encounter with a solar-mass star at an impact parameter of 2100 AU, as expected based on the abundance and velocity dispersion of stars in the solar neighborhood, leads to a quadrupole moment $C_2 = 4.5(3.5)\times 10^{-15},\ 6.7(1.1)\times 10^{-12},\ 1.1(0.11)\times 10^{-9}$ at $\nu = 30, 353, 545$ GHz, respectively in intensity and (temperature) fluctuations. We also quantify the quadrupole spectral distortions produced by the Scattered Disc, which will exist irregardless of any perturbation and the subsequent shape of the Oort Cloud. For comparison, the temperature fluctuation quadrupole moment predicted by the current cosmological model is $C_2 = 1.76\times 10^{-10}$, which corresponds to fluctuation in the CMB intensity of $C_2 = 2.9\times 10^{-10},\ 6.8\times 10^{-9},\ 1.6\times 10^{-8}$ at $\nu = 30, 353, 545$ GHz. Finally, we discuss how a measurement of the anisotropic spectral distortions could be used to constrain the trajectory of the closest stellar fly-by.

## 1. Introduction

At the outer edge of the Solar System exists a swarm of small icy rocks known as the Oort Cloud (Oort, 1950; Dones et al., 2004). Comets with long orbital periods, $P \geqslant 200$ yr, are ejected from this cloud into the inner Solar System by the perturbations from passing stars, giant molecular clouds or tides from the Galactic disc. The perturbed comets are moved onto nearly-parabolic orbits which approach the Sun, develop comae and may be detected. Gravitational perturbations by the planets can strongly alter the comets' orbits as they enter the inner Solar System, and so typically they either get ejected from the Solar System or left strongly bound to the Sun. It is very unlikely that a comet will return again on a nearly parabolic orbit. The observed continual flux of long-period comets on nearly parabolic orbits originally led Oort (1950) to propose that all long-period comets were entering the inner Solar System for the first time and therefore a reservoir of comets must exists in the outermost region of the Solar System.

There is considerable interest in studying the Oort Cloud since it is a remnant of the formation epoch of the Solar System. This is true for both the individual objects, whose chemical composition may reveal information about the composition and thermal state of the outer regions of the proto-planetary disc (but see Mumma et al. (1993) for a comprehensive review of processes that may cause significant evolution in these properties over the past 4 Gyr) as well as the dynamical structure of the Oort Cloud as a whole. The cloud structure, which is largely determined by its formation scenario, may retain information about the masses of the giant planets, the rate at which passing stars perturbed the comets' orbits and the surface density of any gas that was potentially still within the Solar System. This information could provide important clues about the formation processes of the outer planets.

The Oort Cloud is cruedly divided into an inner and an outer region. This division stems from the fact that the probability for ejection into the inner Solar System by external perturbations is a strong function of semi-major axis (Heisler and Tremaine, 1986; Dones et al., 2004). All of the observed long-period comets are believed to have originated from the outer Oort Cloud. The perturbations that eject comets into the inner Solar System also isotropize the comets' orbits and eliminates any information about the formation epoch in the structure of the outer Oort Cloud. Therefore the reduced sensitivity of the comets in the inner Oort Cloud to these external perturbers is both good and bad. On the one hand it leads us to suspect that the structure of the inner Oort Cloud should retain an imprint of its formation as well as any rare, strong gravitational scattering event that might have occured over the past 4.5 billion years. On the other hand, it makes studying the inner Oort Cloud difficult. It is impossible to directly observe the comets in the inner Oort Cloud through their reflected sunlight because they are too far. Extremely large objects like Sedna can be optically detected when they are close to perihelion (Brown et al., 2004), however it will be difficult to detect the potentially large number of small objects ($R \leqslant 1$ km) in this region. One novel

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technique involves using the microwave emission from these bodies to constrain, or possibly detect, the bulk properties of objects in this region (Babich et al., 2007).

At a distance $D$ from the sun an Oort Cloud object will be heated by the Sun to an equilibrium temperature,

$$T_{\rm Oort} = \left(\frac{(1-A)L_\odot}{16\epsilon\sigma\pi D^2}\right)^{1/4} \tag{1}$$

$$\simeq 8.5\,{\rm K}\sqrt{\frac{1000{\rm AU}}{D}}, \tag{2}$$

here we adopted an albedo of $A = 4\%$ (Jewitt and Luu, 1998) and an emissivity of $\epsilon \simeq 1.0$. We adopt a model such that the emissivity of an Oort Cloud object is approximately unity when its size is larger than the wavelength of the relevant radiation and zero when the wavelength is larger. Also, $\sigma$ is the Stefan–Boltzmann constant and $L_\odot = 3.83\times10^{33}$ ergs s$^{-1}$ is the Solar luminosity. The equilibrium temperature is higher than the cosmic microwave background (CMB) temperature of $T_{\rm CMB} = 2.725$ K (Mather et al., 1999). When the comets are farther away from the Sun a variety of physical processes help maintain temperatures greater than $5--6$ K (Mumma et al., 1993). The Oort Cloud objects extinguish some fraction of the CMB radiation and emit blackbody radiation at a higher temperature (Babich et al., 2007). The observed intensity of the CMB radiation is then

$$I_\nu(\hat{\boldsymbol{n}}) = [1-\tau(\hat{\boldsymbol{n}})]B_\nu[T_{\rm CMB}(\hat{\boldsymbol{n}})] + \tau(\hat{\boldsymbol{n}})B_\nu[T_{\rm Oort}(\hat{\boldsymbol{n}})], \tag{3}$$

where $\tau$ is the optical depth and $T_{\rm Oort}$ is temperature of the Oort Cloud objects along the direction $\hat{\boldsymbol{n}}$. (Babich et al., 2007) constrained the mean, or monopole, contribution to the CMB spectrum using the *Cosmic Background Explorer Far Infrared Absolute Spectrophotometer* (COBE FIRAS) data (Fixsen et al., 1997; Mather et al., 1999) and placed upper limits on the total mass in the inner Oort Cloud for a variety of models of the size distribution of Oort Cloud objects. In this paper we will focus on effects that can make the Oort Cloud non-spherical and subsequently produce anisotropic spectral distortions in the CMB.

We should emphasize that the induced spectral distortions considered in this paper are not the chemical potential ($\mu$) or Compton-y spectral distortion that are commonly discussed in the literature. The signal produced in the outer Solar System is that of a sum of weighted blackbodies at different temperatures, which in general does not have a blackbody frequency spectrum. The exception is the Rayleigh–Jean's portion of the spectrum, where the weighted sum of blackbodies does produce a frequency spectrum described by a Rayleigh–Jean's distribution at a weighted temperature. This implies that low frequency data will not be very useful in allowing us to detect a signal originating from the outer Solar System. See (Babich et al., 2007) for a discussion of techniques to distinguish the spectral distortions produced in the outer Solar System from those caused by the CMB temperature anisotropies.

The Oort Cloud is believed to be nearly spherical based on the statistics of the inclination angles of new long-period comets (Marsden and Sekanina, 1971). The observed apsides of these comets are not uniformly distributed across the sky, however the observed clustering trends are believed to be due to the structure of the Galactic potential (Delsemme, 1987; Dones et al., 2004). The Oort Cloud has been populated by objects that formed in the Sun's proto-planetary disc and were scattered multiple times by the four giant planets into increasingly higher eccentricity and higher energy orbits. This process continued until some external perturbation lifted the comets' perihelia well beyond Neptune's orbit, and then the comets became decoupled from the inner Solar System. The radial distribution of the Oort Cloud comets, which is set by how far the gas giant planets can scatter the comets before their perihelia is lifted safely outside the inner Solar System, strongly depends on the external environment of the young Solar System. The evolutionary processes that lifted the perihelia of comets beyond the planetary region of the Solar System must have also made spherical the distribution of comets which where initially in the Ecliptic Plane. Simulations of this formation process have found an inner edge of the Oort Cloud, defined as the semi-major axis at which the comets are isotropically distributed, near $a = 3000$ AU (Duncan et al., 1987) and $a = 5000$ AU (Dones et al., submitted for publication). It should be emphasized that objects with smaller semi-major axes exist, but may be more confined towards the Ecliptic Plane. This is the Scattered Disc which smoothly extends from the flattened Kuiper Belt to the spherical Oort Cloud. We will quantify the effect of the Scattered Disc by calculating the quadrupole moments of its thermal emission. This will exist irregardless of any externally induced asphericity in the Oort Cloud.

An increasing body of evidence now suggests that the Solar System did not form in isolation, but in a stellar cluster which subsequently evaporated (Adams and Laughlin, 2001; Hester et al., 2004). This is not surprising since most low mass stars are observed to form in clusters that subsequently evaporate when the interstellar gas, which is required to gravitational bind the cluster, is expelled from the cluster by either stellar winds or supernova feedback (Lada and Lada, 2003). Beyond this general trend, anomalous abundance ratios are observed in the Solar System that would indicate that a Type II supernova occur somewhere in the vicinity of the Solar System during its infancy (Looney et al., 2006). With a higher number density of stars in the cluster the rate of external perturbations would have been higher and the spherical inner edge of the Oort Cloud would have extended to smaller semi-major axes.

In this paper we will consider the dynamical effect that a star passing within $\lesssim 1$ pc of the sun would have had on the Oort Cloud. And we calculate the signatures that would be produced in the CMB frequency spectrum. The outline of this paper is as follows. In Section 2 we describe how a non-spherical distribution of Oort Cloud objects may affect the measured brightness distribution of the CMB on the sky. In Section 2.1 we calculate the variance of the Oort Cloud signal due to Poisson fluctuations, whereas in Section 2.2 we describe the initial distribution of Oort Cloud objects. In Section 2.3 we outline of method of calculation the perturbations in the orbital elements of the Oort Cloud objects, and in Section 2.4 we calculate the distribution of impact parameters of stellar perturbers. In Section 3 we derive an formula based on the collisionless Boltzmann equation that allows us to analytically estimate the resulting quadrupole distortion from a perturbation. Our results are discussed in Section 4. In Section 5 we develop a Bayesian estimator that can be used to constrain the parameters of a stellar encounter from the observed CMB data. Finally Section 6 summarizes our main conclusions, Appendix A derives relationships between various measures the quadrupole moment and Appendix B describes the model of instrumental noise for the Planck satellite.

## 2. Calculation

We start by calculating how the non-sphericity of the Oort Cloud affects the measured angular distribution of the CMB intensity. The fluctuation in the CMB frequency spectrum along a given direction

$$\delta I_\nu(\hat{\boldsymbol{n}}) \equiv I_\nu(\hat{\boldsymbol{n}}) - B_\nu(\overline{T}_{\rm CMB}), \tag{4}$$

can be expressed as

$$\delta I_\nu(\hat{\boldsymbol{n}}) = \Delta T(\hat{\boldsymbol{n}})\frac{\partial B_\nu(T)}{\partial T} + f_A\int {\rm d}x_i p(x_i)\frac{1}{D(x_i)^2}[B_\nu(T_{\rm Oort}(x_i)) - B_\nu(\overline{T}_{\rm CMB})], \tag{5}$$