Sunyaev-Zeldovich decrements with no clusters?

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ABSTRACT

Sunyaev-Zeldovich decrements in the temperature of the Cosmic Microwave Background (CMB) are produced by Thomson scattering of the CMB photons by the confined hot electrons in the Intra-Cluster Medium encountered along the line-of-sight. In this paper, we propose an alternate physical process that can produce detectable thermal and kinematic Sunyaev-Zeldovich decrements around quasars or quasar pairs in regions where no assembled, virialized clusters are detected either in the optical or X-ray wave-band. Invoking quasar outflows, we argue that both thermal and kinematic decrements can be produced by the baryons swept up by the mechanical luminosity of quasars. In contrast to the case of decrements produced by the hot electrons confined within the cluster potential, the magnitude of these quasar-outflow induced effects depend primarily on the luminosity of the QSO, and the physical scale of the outflow - which in turn depends both on the mean local density and the density gradient in the vicinity of the quasar. Quasar outflows produce (i) a frequency independent kinematic decrement $\Delta T/T \sim 10^{-4}$; (ii) a frequency dependent fluctuation in the intensity $\Delta J_{\nu}/J_{\nu} \sim$ a 20% variation relative to $\Delta T/T$, say at 15 GHz and 30 GHz; (iii) a temperature increment $\Delta T/T \sim 10^{-4}$ on the opposite side of the QSO; (iv) a linear polarization signal over 20” at $\sim 10^{-7}$ level; and therefore (v) patches of signal $\Delta T/T \sim 10^{-4}$ on degree scales which will contribute to the power and hence affect the CMB multipole calculations in the rising region of the first Doppler peak at $l \sim 60$ for CDM-like models as well as defect models. These effects are of interest since they are potentially observable in the context of the next-generation of CMB experiments - MAP & PLANCK.

Key words: cosmology: cosmic microwave background – diffuse radiation – galaxies: quasars – general

1 INTRODUCTION

Sunyaev-Zeldovich decrements in the cosmic microwave background are produced by the Thomson scattering of the photons by hot electrons - typically by electrons that are confined in the dark matter potential well of a rich cluster of galaxies. However, we demonstrate in this work that comparable temperature decrements can be produced by electrons that are swept up by the outflows powered by the mechanical luminosity of quasars. While the properties of the outflow are determined primarily by the energy output of the QSO, the kinematics at late times are determined by the mean density and the density gradient in the vicinity of the QSO. Since in variants of the standard CDM (cold dark matter) dominated cosmological models, quasars form from the collapse of high-significance peaks and tend to seed the high density regions which subsequently are the sites for the formation of clusters, the physical scale of the outflow depends on the ambient density and depth of the local potential well. There are at present many new observations of the CMB in the millimeter wave-band planned or underway, and there is renewed interest in the radio morphology of high-redshift QSOs and their hosts. In this paper, we expand on the classical S–Z scenarios (clusters, clusters with peculiar velocities, relativistic corrections to the scattering cross-sections and warm bubbles around QSOs with finite peculiar velocity) and include another class of objects that may produce such decrements. For this class of objects: quasar outflows, it is instructive to point out that the gas need not be very hot in order to produce an observable decrement. In particular, when the cooling/expansion time-scales are interestingly long, i. e. if the cooling time is comparable to or exceeds the time-scale of the high luminosity phase of the QSO, the effects of the gas can be observed well after the QSO has faded.

This paper is organized as follows: in Section 2 we motivate the role of quasar-driven outflows; in Section 3 the energetic constraints in terms of the implied physical scales out to which the outflows and their effects are likely to manifest themselves are outlined; in Section 4 we discuss the kine-
matic and the thermal S–Z decrement induced by outflows and their other observational implications; and we present our conclusions and prospects for detection in the final section.

2 QUASAR-DRIVEN OUTFLOWS

The ubiquity and high luminosity of quasars out to high redshifts suggests that they might have played an important role in the subsequent formation of structure (Efstathiou & Rees 1988; Rees 1993; Silk & Rees 1998). Babul & White (1991) suggest that the ionization produced by UV photons from the quasar might inhibit galaxy formation in their vicinity due to the ‘proximity’ effect. Thus quasar activity is likely to be one of the important non-gravitational processes to have influenced structure formation at redshifts $z > 2$.

We propose quasar-driven outflows as a possible physical mechanism for concentrating baryons. Such a scenario has been explored previously in the context of explosion induced structure formation models (Ostriker & Cowie 1981; Daly 1987) as well as in theoretical models of the InterStellar Medium (McKee & Ostriker 1977). Mechanically powered outflows can push baryons around active quasars in shells cleaning out regions of $R_{\text{infall}} \geq 1 \text{Mpc}$. We examine the effectiveness of this mechanism in the production of massive clumps of baryons that can in turn produce a signal in the CMB. The observational evidence for these outflows are seen in a subset of radio-quiet QSOs - the broad ab-

3 ENERGETICS OF THE MECHANISM

The total energy available to power a quasar can be directly estimated from the mass accreted by a black hole of mass $M_{\text{bh}}$ (modulo an efficiency factor, $\epsilon$). In general, the total energy available is $10-20\%$ of the rest mass of the central black hole ($\epsilon \sim 0.1 - 0.2$). We assume that roughly $50\%$ ($\epsilon_L \sim 0.5$) of the total energy in turn might be available as mechanical power. By assumption this sets up an outflow that is primarily mechanically powered, that is, a fraction of the energy emitted by the active quasar gets efficiently converted into kinetic energy of the intergalactic medium. Mechanical luminosities up to $10^{47}\text{erg s}^{-1}$ at redshifts $z \geq 4$ for such QSOs are postulated, this is not entirely implausible given inferred X–ray luminosities of comparable magnitude for high $z$ QSOs (Elvis et. al 1994). Clearly such energy coupled locally to the environment as mechanical luminosity would set up an outflow that sweeps out a region of scale $R$:

$$R \sim 1 \left( \frac{\epsilon L}{0.05} \right) \left( \frac{M_{\text{bh}}}{10^{11} \text{M}_\odot} \right) \left( \frac{f_Q}{1} \right) \left( \frac{v}{c} \right) \left( \frac{0.01}{\text{Mpc}} \right).$$  

For our purposes typical swept up regions are of the order of $0.1-1$ Mpc or so; $f_Q$ is the local baryon fraction in units of 0.01, and a density contrast of $\sim 10^3$ over the mean cosmological density at redshift $\sim 3$ is required for the numbers to be consistent, this is a plausible over-density for the highest significance peaks that will seed the massive clusters observed at lower redshifts. The total energy budget $E_T \sim \epsilon \epsilon_L M_{\text{bh}}$; and the restrictions on the available parameter space in terms of the mass that needs to be swept up and the bulk velocity required to produce a kinematic S–Z decrement are dictated by the following relations,

$$\frac{\Delta T}{T} \sim \frac{\tau \nu_{\text{sweep}}}{c} \sim \frac{M_{\text{sweep}}}{M_{\text{c}}} \nu_{\text{sweep}};$$

where $t_{\text{QSO}}$ is the quasar lifetime and $\tau$ the optical depth. Beam dilution imposes a minimum $M_{\text{sweep}}$ assuming the line of sight length through the gas is comparable to its transverse scale, which is likely for the resulting outflow geometry studied here. Scaling to typical Abell cluster parameters, the mean electron thermal speeds are $v_T = v_T/c \sim 0.1$. Since the kinematic effect is first order in $\beta_K = v/c$, we require $\beta_K \approx \beta_T^2 \sim 10^{-2}$. This is consistent with speeds required for the mass of swept up gas which would produce the required optical depths over angular scales of a few arc minutes. It is these mass and velocity requirements which drive us to postulate ultra–massive central black holes to power the outflows. Note that $\tau \sim n_e R$ whereas the mass swept up $M_{\text{sweep}} \sim n_e R^3$. All the numbers quoted in this work have been computed for $H_0 = 50 \text{km s}^{-1} \text{Mpc}^{-1}$; $\Omega_0 = 1.0$ and $\Lambda = 0$. As illustrated by eqns. 2 and 3, the best sources for large energy effects are the massive BHs that power the QSOs. We also note here that according to some models of unified schemes for AGNs, jets and efficient energy release occurs only if the QSO is accreting close to or at super–Eddington rates, possibly via the Blandford-Znajek mechanism for rotating BHs. This might preferentially happen at high redshift, where a higher fraction of high luminosity QSOs are observed, consistent with a picture wherein the most massive BHs form rapidly at high redshift and are fueled by the baryons that are present in these high-density regions. We do not necessarily need fully assembled, virialized dark halos for this to happen, we only need an efficient way to funnel the baryons already there to the bottom of the deepest potential wells.

3.1 Dynamics of the quasar outflow

The outflow starts out being collimated close to the source and has some, small, opening angle so that it does not terminate or disrupt the accretion process which is its powerhouse. At a distance of $\geq 10 \text{kpc}$ away from the central engine, the flow opens out. The mass $M_{\text{sweep}}$ (of the IGM) swept out by the outflow is:

$$M_{\text{sweep}} \sim L_{\text{QSO}}; \nu_{\text{sweep}} \sim \sqrt{L_{\text{QSO}}},$$

where $L_{\text{QSO}}$ denotes the mechanical luminosity of the QSO. As was shown by Phinney (1983), jets from QSOs start out
mildly relativistic with a Lorentz factor \( \sim 1 \); it is likely that the initial outflow is dominated by a pair plasma. The total momentum that the outflow can deposit is determined primarily by the ratio of \( M/\rho \) and therefore bulk speeds of the order of \( v \sim 10^2 c \) are expected, which are indeed observed at low redshifts even in low power radio galaxies like NGC 315 (Bicknell 1994). The mass swept out by a single QSO with an outflow assuming that 50% of its total bolometric luminosity is expelled mechanically is,

\[
M_{\text{sweep}} \sim 2 \times 10^{14} \left( \frac{L_{\text{QSO}}}{10^{48} \text{erg} \text{s}^{-1}} \right) \left( \frac{\delta t}{5 \times 10^8 \text{yrs}} \right) \\
\times \left( \frac{v_{\text{sweep}}}{3000 \text{km s}^{-1}} \right)^{-2} M_\odot ,
\]

(5)

where \( \delta t \) is the duration of the outflow phase, \( v_{\text{sweep}} \) the ejection velocity and \( L_{\text{QSO}} \) the mechanical luminosity of the QSO. The total mass swept up is strictly bounded,

\[
M_{\text{sweep}} \leq \frac{2 \times 10^{14} \left( M_{\text{bh}} / c \right)^2 \epsilon_f L_{\text{QSO}}}{v_{\text{sweep}}^2}
\]

(6)

While the initial outflow is likely to be a pair plasma, the number density of electrons in the bulk outflow is dominated by the swept up hydrogen from the IGM and is estimated as,

\[
n_e \sim 1 \times 10^{-2} \left( \frac{M_{\text{sweep}}}{2 \times 10^{14} M_\odot} \right) \left( \frac{R_1}{1 \text{Mpc}} \right)^{-3} \text{cm}^{-2},
\]

in good agreement with typical values obtained using the 151-MHz and 1.5-GHz data set of Leahy, Muxlow & Stephens (1989). The optical depth \( \tau \) to Thomson scattering is:

\[
\tau \sim 10^{-2} \left( \frac{n_e}{10^{-2} \text{cm}^{-3}} \right) \left( \frac{R_1}{1 \text{Mpc}} \right).
\]

(7)

With an approximate slab geometry as predicted in this outflow picture the gas mass required for a given optical depth can be several times smaller than that for an isothermal sphere whose virialized core provides the most of the optical depth for the clusters S–Z effect. No dark matter is swept up, so the total mass involved is considerably less than the total cluster mass of a virialized cluster producing a comparable S–Z effect. As is evident from our approach, the micro-physics of the early stages of the jet propagation have not been computed in detail. We assume that the flow is initially collimated and breaks out on a scale of a few kpc and that approximately 50% of the energy released due to accretion is efficiently mechanically coupled to the environment. The geometry of a typical region through which the outflow propagates is assumed to be a cosmologically overdense region with a strong external density gradient. Physically, this is required so that the initial outflow can remain collimated right out to the advancing surface where the bulk of the energy is deposited. The advancing surface breaks out and expands once a critical ambient pressure is attained and the presence of the density gradient serves to anisotropize (i.e. destroys the spherically symmetry of) the post break-out expansion.

### 4 S–Z DECREMENT PRODUCED BY THE OUTFLOW

The S–Z decrement in the temperature of the CMB is produced by Thomson scattering of the CMB photons by hot electrons encountered along the line-of-sight (Sunyaev & Zeldovich 1970; 1972; 1980). The magnitude of the decrement is independent of the redshift of the hot plasma and is given by the integral of the pressure along the line-of-sight. The effect has two components a thermal and a kinematic one (Sunyaev & Zeldovich 1980).

#### 4.1 The Kinematic S–Z effect

Coherent streaming motion with a velocity \( v_{\text{sweep}} \) with respect to the frame of reference in which the CMB is isotropic introduces a Doppler shift in the scattered radiation producing the *kinematic effect* which additionally perturbs the temperature and intensity across the region. This kinematic piece induces a frequency independent temperature gradient but a frequency dependent fluctuation in the intensity; both of which have the same sign (determined by the direction of the velocity vector; note that if the outflow is spherical on large scales the kinematic S–Z effect cancels as the line of sight passes through regions with opposite sign radial velocity). Sunyaev & Zeldovich (1980); Peebles (1993), show that the decrement produced by the kinematic term is given by,

\[
\frac{\Delta T}{T} \approx -\tau \left( \frac{v_{\text{sweep}}}{c} \right)^2 ; \frac{\Delta J_\nu}{J_\nu} = \frac{\Delta T}{T} \frac{x \exp(x)}{\exp(x) - 1},
\]

(8)

where \( x = \frac{\Delta T}{T_0} \); the kinematic decrement is first order in \( v_{\text{sweep}}/c \) compared to the normal second order thermal effect produced by hot cluster gas. For typical values of the optical depth and the velocity of the outflow assumed in the above analysis, this yields a \( \Delta T \sim 3 \times 10^{-14} \). We stress here that the *ratio of the predicted thermal to the kinematic S–Z effects depends entirely on the bulk velocity and mean temperature of the plasma*. Below we estimate the thermal component of the S–Z effect expected from a fiducial outflow.

The material at the working surface may be shock-heated to temperatures as high as \( 10^7 \) K, but may cool down efficiently as we argue below. The bulk of the mass (which is the material in the IGM; note that only roughly a thousandth of the mass is expelled directly from the QSO) however is expected to be in a cooler phase. The shock heated dense plasma will cool to a temperature \( T_0 \) such that its cooling time \( t_{\text{cool}} \sim t_{\text{dyn}} \), where \( t_{\text{dyn}} \) is its dynamical time (Rees & Ostriker 1977). Thermal bremsstrahlung is expected to be the primary process for energy loss in the early stages of the evolution of the bubble and X-ray fluxes \( \lesssim 10^{44} \text{ergs}^{-1} \) are expected, which could be detectable for low-redshift bubbles (see Natarajan, Sigurdsson & Silk 1998 for a more detailed discussion). X-ray cooling is inefficient.
for these high power outflows. The plasma can cool to lower temperatures rapidly via turbulent mixing which will tend to homogenize the temperature of the material on the dynamical time-scale. Synchrotron cooling is however, unlikely to be important, since for the typical estimated value of the IGM magnetic field at high-redshifts $|B_{\text{IGM}}| \sim 10^{-8-5} \text{G}$ (see Kronberg 1994) the cooling time exceeds both the Hubble time and the lifetime of the QSO, therefore, unless there are significantly stronger B fields on very small scales energy losses via synchrotron processes will be negligible. The thermal S-Z decrement produced by this warm plasma is:

$$\Delta T / T = (\frac{2 k T_e}{m_e c^2} \tau) = 3.45 \times 10^{-6} \left(\frac{T_e}{10^8 \text{K}}\right),$$

much lower than that expected for virialized gas in a core of a cluster of galaxies. For a range of frequencies, in Fig. 1, we plot the ratio of the expected kinematic and thermal components for the plasma in the outflow. As shown by Birkinshaw (1996), the ratio of the thermal to the kinematic effect is independent of the optical depth and can be written as,

$$\frac{\Delta T_K}{\Delta T_T} = 40 \left(\frac{v_{\text{sweep}}}{3000 \text{ km s}^{-1}}\right) \left(\frac{T_e}{10^8 \text{K}}\right)^{-1},$$

therefore, the contribution from the kinematic effect could easily be one or even two orders of magnitude higher than the thermal effect, for warm ($T \sim 10^6 \text{K}$) plasma with significant bulk motion, as postulated here.

This mechanism might be relevant to a recent detection of a decrement in the region of the quasar pair PC1643+4631 where no cluster is detected. The reported observation was obtained by Jones et. al (1997) using the Ryle telescope at 15-GHz in the direction of the quasar pair PC1643+4631 A&B. The pair separation on the sky is $\sim 200''$ and their $r_4$ magnitudes are 20.3 and 20.6 respectively. The redshifts of the quasars are (A) $z = 3.79$ and (B) $z = 3.83$ (Schneider, Schmidt & Gunn 1994). The central value of the measured decrement is 560 $\mu$K. Interpreting the source as a cluster at $\sim 5$ keV, Jones et. al estimate the implied gas mass to be $\gtrsim 2 \times 10^{14} \text{M}_\odot$ and conclude that the result demonstrates the existence of a massive high redshift ($z \gtrsim 1$) system. However, serendipitous and pointed ROSAT PSPC observations (Kneissl et. al 1997) as well as ground-based optical follow-ups (Saunders et. al 1997) have failed to reveal a cluster of galaxies as the source of the hot plasma to produce this ‘cold’ spot in the CMBR. The hypothesis of lensing by an intervening massive cluster is therefore hard to justify. Another S-Z decrement has been measured at 15-GHz in the direction of the quasar pair PC1643+4631 by Richards et. al 1996, also around a pair of radio-quiet QSOs at a projected separation of 1 Mpc. In this case the pair have the same redshift ($z = 2.561$) and although their spectral features are not identical their velocity separation being small, they are likely to be a lensed pair split by a high-redshift cluster with a large time delay of the order of 500 years. The physical scales involved in both these observations are consistent with the role of quasar outflows and therefore our proposed model might provide a possible physical explanation.

\subsection{4.2 The Thermal S-Z effect}

\subsubsection{4.2.1 Emission from the shock-heated bubble}

In a recent analysis Aghanim et. al (1996), consider another scenario where the kinematic S-Z effect is also much higher than the thermal S-Z effect. They consider the bulk motion of highly ionized baryons in the proximity of QSOs at speeds of $\sim 300 \text{km s}^{-1}$ and at temperatures of $\sim 10^5 \text{K}$, essentially stationary bubbles around the QSO moving with the QSO at the local peculiar velocity. Although the physical picture that we present above is entirely distinct from that proposed by Aghanim et. al, we find the same scaling of the decrement with the relevant parameters:

$$\frac{\Delta T}{T} \sim 3 \times 10^{-4} \left(\frac{\tau}{10^{-2}}\right) \left(\frac{v_{\text{sweep}}}{3000 \text{ km s}^{-1}}\right) \left(\frac{L_{\text{QSO}}}{10^{48} \text{erg s}^{-1}}\right)^{1/2} \left(\frac{1+z}{1+3}\right)^{2/3}.$$ 

The magnitude of the kinematic S-Z effect from outflows scales primarily with the mechanical luminosity of the QSO and the redshift, therefore, we expect stronger decrements preferentially from high luminosity and high redshift QSOs. Bicknell (1994) finds for a local FRI radio galaxy NGC 315, $\beta \sim 0.15 \text{M}_\odot$; our model considers QSOs that are essentially the high-redshift, scaled-up (scaled up in luminosity and hence the physical scale on which the outflow occurs) versions of objects like NGC 315.

We stress here that spherically symmetric outflows do not generate a kinematic S-Z signal, an anisotropy induced
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By the bubble expansion into a density gradient is required. More importantly with every observed kinematic S–Z decrement a corresponding increment is produced due to the opposite sign bulk velocity on the other side of the QSO.

Several immediate predictions follow from our proposed scenario: while the temperature decrement is frequency independent, the intensity change is not (shown explicitly in eqn. 8 above), so we expect a ∼ 20% variation in ΔJ/J relative to ΔT/T at say 15 GHz and 30 GHz. We also expect a temperature increment of the same amplitude on the opposite side from the decrement (see the marked ‘hot’ spot HS and the cold spot as CS in Fig. 2), as we expect an outflow with the opposite sign radial velocity on the other side of the QSO.

Since the optical depth τ and v/c are of comparable order, both polarization effects (see Sunyaev & Zeldovich 1980) arising due to (i) the finite angle subtended by the line-of-sight with respect to the velocity vector (linear polarization ∼ 0.1τ(x/λ)²) and (ii) the finite optical depth (circular polarization ∼ ±0.1τ(x/λ)²) are also roughly equal. Therefore, we expect polarization at the 10⁻² level on 20° scales from flow transverse to the line of sight, along the line from the QSO to the peak decrement. Given the density and the temperature of the outflow material, the corresponding X-ray luminosity LX is expected to be ∼ 10¹⁴ erg s⁻¹, below the flux limit of current X-ray observations, and substantially redshifted to lower energies. We also note that the presence of extended cool gas with n_e ∼ 10⁻² as predicted by this outflow picture could be detected via absorption features seen blueward of the emission peak (offset by ∼ 3000 km s⁻¹) in the QSO spectrum. Given the available energy budget, diffuse Lyman-α emission from recombination in the warm gas is expected with approximate surface brightness within a narrow band filter (width ∼ 60 Angstrom) that is of the order of ∼ 25 mas arcsec⁻². Such diffuse emission may be detectable through narrow band imaging or long slit spectroscopy, it is interesting to note that somewhat smaller scale diffuse emission has been seen around both a low redshift, low luminosity radio–loud QSO 4C 03.24 (van Ojikpine et al. 1997) as well as in two high redshift radio–loud QSOs (Lehnert & Becker 1998). The diffuse emission predicted for the QSO pair (PC1643+4631) is of comparable power to that seen around the quasar 4C 03.24, but spread over a larger angular scale due to the greater spatial extent required of the outflow. Any fortuitous alignment of two QSOs such that their outflows contribute additively to the S–Z decrement would make the effect unusually strong and hence detectable. We would expect this effect to be rare in general, even in the proximity of bright, high redshift, radio–quiet QSOs with the optimal opening angle (θ ≈ 45°). It also strongly depends on the efficiency of the conversion of the bolometric QSO luminosity to mechanical outflow with time and environment. The luminosity of radio quiet QSOs is seen to increase strongly with z (Barvainis, Lonsdale & Antonucci 1996; Taylor et. al 1996). For instance, in the scheme of Falcke et. al (1996) the QSOs in PC1643+4631 at their brightest would have been classified as FRIIs with luminosities in excess of 10⁴⁸ erg s⁻¹ (see Falcke et. al’s Figure 1); the radio jets have now faded and the accretion power decreased by many orders of magnitude, possibly due to depletion of the cooling flow in the inner kpc (see eg. Fabian and Crawford 1990) or decreased efficiency at lower mass accretion rates. Since the outflow must not be spherical at large radii for a kinematic S–Z effect to be observable, substantial amounts of gas ought to remain in the vicinity of the QSO in the regions outside the out–flowing cone, and would probably condense into the lyman absorbers or even a population of baryon-rich dwarf galaxies (Natarajan, Sigurdsson & Silk 1998) observed in the vicinity of QSOs.

The presence of bright radio sources in the immediate vicinity could make this effect difficult to detect. In the context of unified AGN models, the viewing angle implied for radio loud QSOs means looking straight down the jet, therefore detection of such extended bulk flows from them is impossible. Hence one would only see such effects after the peak emission had diminished by several orders of magnitude and the extended radio lobes faded.

In order to predict how many such objects are expected to be detected, we need to estimate the number density of QSOs which had strong outflows. If we believe the jet power scalings with luminosity and redshift predicted by models, the relevant number density is then of QSOs with luminosities ≥ 10⁴⁷ erg s⁻¹ within the optimum redshift range z ≥ 1. In order to not violate (the admittedly weakly constrained) local BH mass functions, we expect the ultramasive BHs needed for this scenario to have a mean space density of 10⁻⁷ per Mpc⁻³ or less.

5 CONCLUSIONS

S–Z decrements measured in the vicinity of QSOs where no clusters are detected either in the optical or the X-ray may be due to a concentration of baryons aggregated by the power of mechanical outflows from these quasars. The above phenomenon leads to the following predictions (note that
the numbers below are for the kinematic S–Z decrement caused by the outflow from a single QSO:

- (i) it produces a frequency independent decrement \(\Delta T/T \sim 10^{-4}\);
- (ii) a frequency dependent fluctuation in the intensity \(\Delta I/I \sim 20\%\) variation relative to \(\Delta T/T\) at say 15 GHz and 30 GHz;
- (iii) a temperature increment \(\Delta T/T \sim 10^{-4}\) on the opposite side of the QSO;
- (iv) a linear polarization signal over 20" at \(\sim 10^{-7}\) level (pushing at the limits of the detection by the proposed new instruments on MAP and PLANCK);
- (v) patches of signal \(\Delta T/T \sim 10^{-4}\) on degree scales which will contribute to the power and hence affect the CMB multipole calculations in the rising region of the first Doppler peak at \(t \sim 60\) for CDM-like models as well as defect models;
- (vi) we expect this to be a rare phenomenon, occurring only in 1 – 3 % of all high-redshift QSOs; and finally,
- (vii) the thermal effect is one or two orders of magnitude smaller than the kinematic one.

In principle, the effect ought to be observable for QSOs in cases with the appropriate opening angle and alignment of outflow to the line of sight, and preferentially for high mechanical luminosity, high redshift, radio-quiet QSOs. We note with interest the very large scale diffuse radio emission seen on two sides of A3667 (Röttgering et al. 1997). If the source there is due to outflow from a now quiescent black hole in the central galaxy of the primary cluster, which is one of the possible explanations, then future observations should reveal a supermassive black hole in the cD, primarily through a sharply rising central dispersion in the inner regions of the galaxy. From the scale of the outflow, if it was powered by an AGN outflow, a black hole mass of \(\sim 10^{10} M_\odot\) accreting at near Eddington luminosity for at least a Salpeter time is required, and the activity would have peaked \(\geq 10^9\) years ago.

Since the physical model that we have presented here is speculative, we briefly summarize below the problems presented by the observations of S–Z decrements in QSO fields with no detected clusters:

(i) A wind-driven model composed of a pair plasma is somewhat analogous to the state of the bubble during the early phases of our proposition here but such material is too hot and would have a short lifetime, and, more importantly, the maximal scale out to which such plasma could be swept out is only of the order of \(\sim 100\) kpc, insufficient to explain decrements on large scales \(\sim 1\) Mpc. Furthermore, such plasma should produce easily observable diffuse radio emission as it collides with the IGM. The observational implications of this variant have been discussed in Natarajan, Sigurdsson & Silk (1998).

(ii) It is possible that decrements can be caused by warm gas in the potential well of proto-clusters. The gas would not be in virial equilibrium, such a scenario might fit with the essential outflow model we present here, but in the limit of a more modest spherical outflow. Any detected decrement would then be the signature of the hot gas formed by an asymmetric collision of the unconfined outflowing gas with cold infalling gas. If the inflow is strongly non-spherical, as is likely in unvirialized proto-clusters, this would produce a hot spot, therefore producing a one-sided thermal SZ effect. Such a scenario is therefore easily distinguished from the pure kinematic effect discussed above, as the thermal decrement would show as a strong increment at shorter wavelengths and the predicted long wavelength increment on the opposite side of the QSO would be absent.

Although we have presented a somewhat speculative model, it makes several falsifiable predictions. Our model does require ultra-massive black holes, but that is not forbidden, in fact observations imply precisely that some of the high redshift QSOs have total luminosities in excess of \(10^{48}\) erg s\(^{-1}\), implying central black hole masses of the order of \(10^{10} M_\odot\). We note that the estimated BH mass in the case of the nearby BL Lac OJ287 (Lehto & Valtonen 1996) at \(z=0.306\) is \(\sim 2 \times 10^{10} M_\odot\), and this is unlikely to be the most massive black hole in the universe. How ultramassive black holes could form at high redshift to produce such high luminosity sources; and whether high luminosity QSOs are particularly efficient at producing mechanical outflows are separate issues to be contemplated if further observations are consistent with the model proposed here.

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