Abstract. The limited angular resolutions and sensitivities historically available below 300 MHz have made it difficult to define the low end of the electron energy distribution, N(γ). We extrapolate down from the well observed segments of radio spectra with almost complete ignorance of what N(γ) is actually doing. We do not know if there is a low energy cutoff or if there are other deviations from extrapolated power laws. The result is that we really do not have a good estimate of the total energy density and pressure of the relativistic plasmas we study. The situation is even worse for Inverse Compton (IC) X-ray emission, several flavors of which rely on electrons of Lorentz factors, γ, of 1000, 300, or in some cases of order 50. If our assumed extrapolations are wrong, some IC emission models may have to be abandoned. We present several examples and demonstrate that the Long Wave Array (LWA) should have sufficient sensitivity and resolution to obtain meaningful constraints on N(γ) at low energies.

1. Introduction

At this meeting, we are honoring a man who has not lost sight of his life-long passion for low frequency radio astronomy. Erickson’s exploits are legendary and described in detail in other contributions in this volume. We note that twenty years ago, November 1984, Erickson and Cane organized a Green Bank Workshop on Low Frequency Radio Astronomy and that 10 of the 43 participants of the ’84 workshop managed to survive the intervening 20 years and are registered at this meeting. In section 2, we review what sort of science we were doing at that time, from the point of view of a guest observer with the TPT at the Clark Lake Radio Observatory.

In addition to celebrating Erickson’s birthday, we have come to evaluate and nourish the LWA proposal. In my opinion, if the LWA does nothing more than tell us something new about the low end of relativistic electron spectra, it will have been worth the effort! Thus, in section 3 we review some of the reasons why these low energy electrons are important. Briefly, most of the energy density resides below γ≈5000, i.e. the low end of the electron energy distribution which is generally not sampled by radio observations with arcsec synthesized beams.

In section 4, we focus on several of the IC processes proposed for X-ray emission which rely on the presence of electrons with γ ≤ 1000. What is normally not discussed in the literature is the extrapolation required from the ‘radio-sampled’ section of N(γ) to the energies required for the particular IC model being proposed. We consider various examples of IC X-ray sources and show what LWA
resolutions and frequency coverage could do to mitigate the uncertainty of the current extrapolations.

We use the standard definition of the spectral index, $\alpha$: flux density, $S_\nu \propto \nu^{-\alpha}$.

2. What were we doing at Clark Lake anyway?

The aspect of our previous work at Clark Lake which most relates to my topic here was published in Harris et al. (1988), a multi-wavelength study of 4 fields containing steep spectrum radio sources. We used the Clark Lake TPT at 30 and 57 MHz, the VLA at 1.4 and 5 GHz, the Westerbork Synthesis Radio Telescope at 610 MHz, the Dominion Radio Astrophysical Observatory at 1.4 GHz, and the Einstein Observatory for X-ray data.

The beauty of Clark Lake data was that it made it easy to locate the steep spectrum source since the high flux density at 26 MHz used to select these fields was determined with a beam of $14' \times 92'$. As seen in fig. 1, the source of interest is clearly indicated by the 30MHz map. The 57 Mhz positions were good enough to tie into the higher frequency data so that we could then determine an optical identification, define the source morphology, and obtain radio spectra from 30 to 5000 MHz.

Once we had the source distance, size, and spectrum, we could run the usual numbers for synchrotron models (Pacholczyk, 1970), and obtain equipartition field strengths, relevant energy densities, etc.

A result from that paper was the extrapolation of the electron spectra. We showed that if you believe the extrapolation, the number of electrons in these sources between $\gamma=100$ to 1000 is comparable to that in Cygnus A. If you extend the spectrum down to $\gamma=10$, then there are more low energy electrons in these relatively weak FRI sources than in Cygnus A. These low energy electrons serve as a measure of the integrated luminosity of the source over its active life since they have a very long lifetime.

3. General considerations concerning the low end of $N(\gamma)$

3.1. Uncertainties in the low end of $N(\gamma)$

What happens to $N(\gamma)$ below $\gamma$=a few thousand where we can begin to estimate it from ground based radio observations? Possibilities include:

- $\alpha$ increases to values between 1 and 2 (or more) so that there are many more low energy electrons than we would predict by extrapolating the observed spectrum. For examples of sources with low frequency steep spectra, see Braude et al. (1969) and Roger et al. (1973).

- $\alpha$ remains essentially constant as observed in the cm band so that calculated extrapolations down to $\gamma \approx 10$ give the proper number of low energy electrons.

- The spectrum flattens towards $\alpha=0$ so that there are actually fewer low energy electrons than predicted by the extrapolation.
there is a low energy cutoff between $\gamma = 300$ and 1800 so that there are essentially no electrons at very low energy.

In spite of our almost total ignorance as to which of these conditions occurs, many IC models of X-ray emission rely on the assumption that an extrapolation to low $\gamma$'s based on the observed $\alpha_r$, is valid. The uncertainty as to the form of $N(\gamma)$ also compromises our attempts to determine if the plasma is pair dominated or consists of protons and electrons. Using pressure balance arguments between non-thermal pressures in radio lobes and the ambient medium in clusters of galaxies, we often find that the external thermal pressure is larger than the minimum non-thermal pressure. This could indicate that the relativistic plasma is far from equipartition between field and particles; that the filling factor is much less than 1; that the low energy electrons we are discussing have not been properly estimated; and/or that there is a significant contribution to the energy density from relativistic protons (the “1+k term”). Minimizing our uncertainty on the contribution to the pressure from the low energy electrons serves to strengthen constraints on the proton contribution to the non-thermal pressure.

3.2. Dependence of synchrotron parameters on the lower integration limit of the frequency

To illustrate what we are dealing with, consider the differences resulting from choosing a low frequency limit of integration of 330, 10, and 0.1 MHz. In the following examples, we use the measured flux density at 1.4 GHz of the north lobe of 3C351 with a filling factor, $\phi = 1$, assumed equipartition, and $k = 0$ (no significant contribution from relativistic protons). In figs. 2 and 3 as a function of the low frequency limit of integration, we show the values of $\gamma$; the equipartition field strength, $B_{eq}$; the minimum non-thermal pressure; and the total energy in particles and fields for values of $\alpha$ of 1, 1.5, and 2.
Figure 2. The dependence of the equipartition field strength and the non-thermal pressure on the lower limit of the radio spectrum. The three lines correspond to values of $\alpha$ of 1.0 (solid), 1.5 (dashed), and 2.0 (dotted). The actual flux density used corresponds to that from the north lobe of 3C 351. The left panel is the equipartition magnetic field strength and the right panel is the non-thermal pressure.

Figure 3. The dependence of $\gamma$ and total energy on the lower integration frequency. The left panel shows the value of $\gamma$ of the electrons radiating at the given radio frequency. The right panel shows the total energy stored in particles and fields.

Naturally, $B_{eq}$ goes up to keep pace with the increasing particle energy density as the lower integration frequency decreases and the pressure follows $B_{eq}$.

3.3. What is the evidence for a turnover or cutoff in $N(\gamma)$?
In the case of shock acceleration for plasmas consisting of electrons and protons, there has been a long standing problem of how to get electrons up to the $\gamma$'s
required for diffusive shock acceleration to be effective. Lesch and Birk (1997) argue that this ‘injection energy’ is 1800, although other analyses produce lower values (e.g. 100 to 800, Eilek & Hughes 1991). If these conditions (i.e. protons are present in equal numbers with electrons) pertain to the generation of synchrotron emitting plasmas, there would be little expectation that the observed power law of the radio spectrum would be normally related to the behavior of \( N(\gamma) \) for \( \gamma < 1800 \).

Observationally, Carilli et al. (1991) when fitting synchrotron models to hotspots of Cygnus A had to invoke a cutoff in \( N(\gamma) \) at about \( \gamma = 400 \) in order to accommodate the measured flux densities at 151 and 327 MHz (\( B_{eq} = 300 \mu G \)). SSA explanations suffer from an outrageously large \( B \), or very small filling factor.

Both of these arguments lend credence to the notion that we should not expect our assumed extrapolations to small values of \( \gamma \) to be valid.

4. The IC connection to synchrotron emitting plasmas

Here we focus on IC emission in the X-ray band of 0.2-10 keV, but there are of course many considerations in the literature of IC emission in other bands (e.g. to explain cluster excesses in the extreme ultraviolet and to explain hard (20 to 80 keV) X-rays from clusters of galaxies.

Synchrotron emission depends on the energy density of the magnetic field, \( u(B) \) and IC emission depends on the energy density of the photons, \( u(\nu) \). Both of these are essentially mandatory processes, but IC is ‘more’ mandatory in the sense that every radio source must have at least a photon energy density from the cosmic microwave background, \( u(CMB) \) and the observed \( u(\text{sync}) \), whereas there is no a priori knowledge of the average value of the magnetic field strength or of its spatial variations.

In this section we consider several flavors of IC emission and give a few examples of particular sources and demonstrate how data from the LWA would provide critical sampling of the underlying electron spectra at low energies. For illustrative purposes, we take the LWA resolution to be 15”, 5”, and 2” (FWHM of synthesized beam) at 10, 30, and 75 MHz, respectively. The straw man sensitivity at these 3 frequencies is assumed to be 3, 1.6, and 1 mJy (point source sensitivity for 1 hour integration, 4 MHz bandwidth, and 1 polarization).

4.1. Synchrotron Self-Compton (SSC) Emission

This is the well known process used in blazar cores and in the brightest radio hotspots (Harris, Carilli, and Perley, 1994; Hardcastle et al. 2004) to model X-ray and higher frequency emissions. Unless field strengths are much greater than the equipartition fields estimated, the electrons responsible for the observed X-rays have energies comparable to those required for the observed synchrotron spectrum (typical \( \gamma \)'s of 5000 and greater), so they are not of direct interest here (no extrapolation of the electron spectrum is involved in deriving model parameters).
4.2. IC/CMB Emission from Radio Lobes

Achieving robust detections of IC/CMB X-rays with good signal to noise from radio lobes has been fairly elusive observationally even though we know the emission has to exist. There are however, a growing number of lobe detections with Chandra which generally are in agreement with equipartition field estimates to within a factor of a few. For the soft X-ray band, electron energies of $\gamma \approx 1000$ are required, regardless of the redshift of the source (the shift in the peak of the CMB spectrum compensates for the shift in the observed frequency).

The first example is the northern lobe of 3C 351 shown in fig. 4 for which Hardcastle et al. (2002) report a detection consisting of $59\pm14$ net counts (0.4-7 keV). Since some kind soul has seen to it that the very bright (both in radio and X-rays) hotspots have been positioned well away from the lobe, even the lowest frequency beam of the LWA will be sufficient to measure the lobe intensity.

From the spectrum, it is clear that the LWA sensitivity should provide good s/n even if the spectrum flattens at low frequencies. It is also obvious that the LWA radio data will sample most of the segment of the electron spectrum which is supposed to generate the IC/CMB X-ray emission. Thus the LWA will have sufficient resolution and sensitivity to provide a critical test of the IC/CMB model. The usual train of arguments will then be tightened to give better values of the average magnetic field strength (i.e. the uncertainty as to the validity of the extrapolation of $N(\gamma)$ will no longer be present).

Another example of IC/CMB emission comes from the northern lobe of the radio galaxy, 2048-272 at $z=2.06$. This source is shown in fig. 5 and it can be
seen that at 10 MHz, the LWA beam will include the southern lobe as well as the northern one. This may not preclude obtaining a spectrum for the northern lobe unless the ratio of intensities is a strong function of frequency; a situation that would be obvious from data above 30 MHz where the LWA can separate the components. An X-ray detection of the northern lobe, consistent with IC/CMB emission, is reported in Overzier et al. (2004): $6\pm4$ net counts.

Although the extrapolated spectrum ($\alpha_r=1.79$) is again centered around $\gamma=1000$, because of the stronger B field, LWA will now be sampling $N(\gamma)$ towards the bottom end of the segment responsible for the 0.2 to 5 keV X-rays. The LWA sensitivity provides a comfortable margin to accommodate any turnover in the spectrum. Thus the IC/CMB model can be tested at $z=2$ where the energy density in the CMB is 80 times larger than locally.

![Figure 5](image.png)

Figure 5. The radio galaxy 2048-272 at $z=2.06$ (Overzier et al. 2004). The left panel shows a 5 GHz map from the VLA, again with the predicted beamsizes from the LWA. Contour levels start at 0.2mJy/beam and increase by factors of two. The right panel shows the spectrum, as in fig. 4.

In addition to radio lobes, IC/CMB emission has been suggested from cluster halo sources like Coma. In the soft X-ray band we would again be dealing with electrons with $\gamma \approx 1000$, but the thermal emission swamps the IC signal. IC/CMB has also been suggested for EUV excesses from clusters ($\gamma \approx 300$) and for hard X-ray excesses in the 20-80 keV band ($\gamma \geq 5000$, values similar to the observed radio band).

### 4.3. IC/CMB Emission from Jet Knots with Bulk Relativistic Velocities

Although we take it as self evident that kpc scale jets have a bulk relativistic velocity (with Lorentz factor $\Gamma = (1 - \beta^2)^{-\frac{1}{2}}$; $\beta = \frac{v}{c}$), from the general one-sidedness of many radio, and essentially all detected X-ray jets, there is no direct evidence supporting the large values of $\Gamma$ (i.e. 10 and larger) required for the beaming model of Tavecchio et al. (2000) and Celotti et al. (2001). Essentially all of the models in the literature assume that $N(\gamma)$ can be extrapolated down to the range from $\gamma=10$ to 300 with the power law index, $p=2\alpha_r+1$, which is...
obviously based on the radio spectral index measured at much higher frequencies and hence based on larger electron energies. If there were many more electrons than predicted by the extrapolation, then smaller values of $\Gamma$ would be indicated, and if there is a low energy cutoff of $N(\gamma)$, a much larger $\Gamma$ would be required, and consequently a smaller viewing angle etc. A true exponential cutoff would, of course make the beaming IC/CMB model untenable since there would be no electrons with the proper energy to produce the observed X-rays.

As an example, we show in fig. 6, PKS0637-752, a quasar at $z=0.651$. Although not visible from New Mexico, it is perhaps, the most widely believed example of IC/CMB X-ray emission from a jet purported to have $\Gamma=10$. Unless the core emission is absorbed at low frequencies, the LWA resolution would limit a separation of the jet knot from the core to frequencies of 30 MHz and greater. Although the LWA would not sample electrons with $\gamma \approx 100$ which provide the bulk of the observed X-rays, the 30 MHz data will successfully bridge the gap in the extrapolation. Thus the LWA data would provide a critical and convincing test of the IC/CMB beaming model for X-ray emission from high power, kpc scale jets.

![Image of PKS0637-752](image)

Figure 6. PKS0637-752, a quasar at $z=0.651$. The left panel shows a 5 GHz map from the ATCA (kindly provided by Lovell) with contours from 4 to 1024 mJy/beam increasing by factors of two. The LWA beam widths at 30 and 75 MHz are shown. The right panel shows the spectrum as for previous figures.

4.4. IC Emission from Radio Lobes Illuminated by Quasar IR/Optical

Brunetti (e.g. Brunetti et al. 2001) has suggested that if powerful radio galaxies contain a hidden quasar as in the unified scheme, then it may often happen that the cone of un-obscured quasar emission would illuminate the radio lobes and for those parts of the lobes close to the host galaxy, the IR/optical quasar emission would dominate the local photon energy density. This photon bath would be anisotropic and hence there would be a preference for scattering events to occur when an electron is moving towards the core. This leads to a gentle beaming of the IC X-rays so that the receding side of the source should be brighter in the X-rays. Since the illuminating photons have frequencies of order $10^{14}$ Hz,
to produce the observed X-rays, we need electrons with $\gamma \approx 100$. Only a few examples of this behavior have been given in the literature and actual numerical estimates depend on assumptions about the unseen quasar flux. Thus we will not pursue it further except to state the obvious that once again, we have a substantial extrapolation in $\gamma$ so that the LWA would provide useful data so long as the angular resolution was sufficient.

4.5. IC Emission from Radio Jets Illuminated by Hotspot Radio Emission

Another rather specialized process for high luminosity radio galaxies and quasars was suggested by Georganopoulos & Kazanas (2003). For a model in which a jet maintains a bulk relativistic velocity until it decelerates at the terminal hotspot, the jet will experience a photon energy density from the hotspot radiation amplified by $\Gamma^2$, (the square of the jet’s bulk Lorentz factor before the final deceleration).

As the jet approaches the hotspot this photon energy density will increase to a point where it will dominate other photon fields and be sufficient to increase the ratio of IC to synchrotron emission. The resulting IC X-ray emission will be beamed along the jet direction, and the electrons producing the X-ray emission will have $\gamma$’s typical of those producing the normal band radio emission, so that no extrapolations are required, and hence this process is not of direct interest here.

5. Conclusions

- Will LWA data provide constraints on acceleration mechanisms?
  Yes - to the extent that we can determine $\gamma_{\text{min}}$

- Will these data test any current IC emission models?
  Yes - they will allow us to confirm or to disallow IC/CMB with beaming. If we can demonstrate a low E cutoff, this model will become untenable. The standard interpretation of IC/CMB X-rays from radio lobes will also be tested.

The focus of this paper has been on the uncertainty involved in extrapolating electron spectra to low energies, and the ramifications of discovering that our assumed extrapolations may be wrong. A different outcome however, would be that LWA observations convince us that instead, the extrapolations are valid and that there is little or no change in the observed power law down to low values of $\gamma$. In that case, the IC X-ray data will provide measurements of the amplitude of $N(\gamma)$ for lobes and clusters of galaxies, and constraints on the amplitude and $\Gamma$ combination for jets.

For fairly clean examples of IC/CMB from lobes like 2038-272 and 3C351, we see that data from the LWA will permit us to sample the electron spectra at the same energies that we observe with Chandra via IC X-rays. The IC data provide the amplitude, $k_e$, of $N(\gamma)$ for various values of $\gamma$ below 1500. The synchrotron degeneracy between $B$ and $k_e$ will thus be resolved and we will then
have a good estimate of $<B>$ without the uncertainty of any extrapolation. Furthermore, our estimates of the total energy (in fields and particles), the non-thermal pressure, and the energy density will be much more robust and thus we should begin to answer the question of what is the value of $\gamma_{\text{min}}$. The equipartition constraint will have one less unknown, and pressure balance arguments will then give us constraints on the filling factor and the $(1+k)$ factor (contribution from relativistic protons).

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