The Problems of Ageing

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Abstract

I present a brief overview of observational, modeling and theoretical issues related to ageing calculations based on spectral steepening. These include problems such as inhomogeneous magnetic fields, diffusion of relativistic particles, confusion from multiple particle populations and particle acceleration. Although some of the effects are only of order unity, others call into question the entire ageing paradigm. I refer to and show some data illustrating these problems and make a few recommendations about how we should proceed given these uncertainties.

1 Introduction

The relative depletion of high energy relativistic electrons due to radiative losses, either by the synchrotron or Inverse Compton mechanisms, is a well-understood physical process. It is likely to explain the almost universal observation that at sufficiently high frequencies, the broadband spectra of extragalactic radio sources fall below the power-law extrapolation from lower frequencies. From this observation, with a large number of assumptions, it is possible to derive an age for the relativistic electron population, usually representing the time since the particles were last accelerated.

Before addressing the problems with how such age estimates are made, let’s first look at why, and at what level of accuracy, age estimates become important. This issue has received little, if any, discussion in the literature. Most importantly, radiative ages provide a basic confirmation and constraint on the physical models of extragalactic sources. E.g., where particle lifetimes are demonstrably short, we typically invoke \textit{in situ} particle acceleration. This leads us to physical models including shocks or turbulence or “freezers” (Owen, 1997).

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Radiative ages, whether short or not, can also be useful for comparison with estimates derived from other methods, e.g., energy supply, dynamics, or evolutionary models. For all of the above, radiative ages within a factor of a few are probably sufficient.

2 Overview of Ageing Problems

To understand the fundamental ways in which ageing calculations may be wrong, it is useful to characterize the standard and alternative pictures of the evolution of the relativistic electron population. In the standard model, particles are accelerated to high energies in nucleus, jets, and hot spots. Downstream steepening of the spectra indicate radiative energy losses of an initially homogeneous electron population. In an alternative picture, particles that are injected to the downstream flow from nucleus, jets and hot spots have a range of particle acceleration histories; all have already experienced radiative losses. Downstream steepening or flattening occurs through magnetic field and adiabatic variations, further particle acceleration, inhomogeneities and perhaps further radiative losses (although the last may not be necessary).

Observationally, there is a fundamental degeneracy in that many plausible factors can mimic the appearance of radiative losses. In such cases, standard ageing analyses can be made but would have no meaning. Steepening of the radio spectrum with distance from the nucleus or a hot spot might be due to overall variations in the magnetic field strength, adiabatic losses of electron energies and field strengths, changes in the filling factor of high field regions, the onset or decline of efficient particle acceleration, changing mixtures within a beam of otherwise non-evolving particle populations, in addition to the almost universally invoked radiative losses. There is increasing evidence, on both theoretical and observational grounds, that these confusing effects are not simply pessimistic speculations but actually occur.

It is important to remember that most measurements of ageing are based on a second order effect, namely the change in the observed spectral index from one location in the source to another. So while it is likely that losses at some time and place have probably caused the observed curvature in the spectrum, it is much less clear whether local variations in spectral index reflect subsequent particle energy losses and gains.

Most of the ideas presented here are not new. Questions regarding the validity of radiative age estimates have a long history of being proposed and forgotten, largely because of the complications of dealing with them. Quick on the heels of the discovery of M87’s optical synchrotron jet, Felton (1968) pointed out that relativistic particle acceleration must take place in situ (cf (Heinz &
By the mid-70s, the increasing number of bridges with spectral gradients allowed ageing analyses to become popular (e.g., Jenkins & Scheuer (1976)). During this period Willis & Strom (1978) suggested the need for in situ acceleration in giant radio galaxies.

Enormous progress was made in spectral mapping programs in the 1980s. Among the problems raised, Alexander & Leahy (1987) pointed out that derived ages did not extrapolate to zero at the hotspots, as they should. They suggested that adiabatic expansion losses would shift the break frequency and mimic a finite age immediately post-hot spot. It is disappointing to note that no one has yet taken up the necessary calculation of the radiative evolution of a curved injection spectrum.

The first serious treatments of how temporal changes in the magnetic field or inhomogeneities in the field can affect spectral ages were carried out by Wiita & Gopal Krishna (1990) and Siah & Wiita (1990). Blundell & Alexander (1994) introduced a method for interpreting spectral breaks when both adiabatic and radiative losses are present. Most of this work has been virtually ignored in the literature. During the 1990s, a few workers have explored the relationship between source structure, dynamical ages, and radiative ages. Eilek (1996) has argued that radiative ages are deceptively short, such as will result from emission in highly inhomogeneous magnetic fields (Eilek, Melrose & Walker 1997). Tribble (1993, 1999) has investigated the effects of random magnetic fields on ageing calculations and the effects of electron diffusion on the spectral shape. Kaiser, Dennett-Thorpe & Alexander (1997) have looked in detail at the energy history of radiating particles, another major oversight in the standard analyses.

3 Evidence for Confusion in Radiative Age Calculations

The magnetic field and apparent ageing. We start with the oft-ignored fact that at a fixed observing frequency, $\nu_{\text{obs}}$, we sample particles with a characteristic energy $\gamma_{\text{obs}}$ depending on the local value of the magnetic field, $B_{\text{local}}$, according to $\nu_{\text{obs}} = \gamma_{\text{obs}}^2 B_{\text{local}}$. When the local field changes, so does the energy of the observed particles and their slope (the spectral index) if the underlying electron population is already curved. This generally implies without any additional losses, a consequence of lower $B_{\text{local}}$ will be both a decrease in emissivity and a steepening of the spectral index. This correlation of low brightness and steep spectral index is almost universal, and is strong even at low frequencies where the emissivity is expected to be insensitive to losses (e.g., Leahy, Muxlow and Stephens, 1987). Variations in $B_{\text{local}}$ thus stand as a viable alternative to local ageing. What is needed is a serious, quantitative estimate of the possible effects of these variations in each source where a claim of radiative
ageing is to be made. When we attempted to do this for the steep-spectrum sheaths in two WATs, we were unable to distinguish between variations in $B_{\text{local}}$ and different radiative loss histories (Katz-Stone et al. 1999).

Perhaps the most dramatic example of this problem is seen in the beautiful work of Feretti et al. (1998) on the large scale structure of NGC 1265, who show a plot of intensity and spectral index as a function of distance from the core of this head-tail source. At a distance of 13 arcmin, the intensity drops precipitously by almost an order of magnitude and the spectral index suddenly steepens from $-1.2$ to $-2.2$. These changes are certainly unrelated to ageing, and likely result from a sudden drop in the magnetic field strength along the flow or a completely separate electron population. When one looks at the more gradual brightness declines and spectral steepening in the first 13 arcmin, it is then proper to ask whether gradual radiative losses or magnetic field reductions or both are responsible.

Another major problem arises from our untested assumption that the energy densities of relativistic electrons track those in the magnetic fields. This directly influences our calculations of magnetic field variations and radiative ages across a source. There are a variety of circumstances in which this would not be true. We are on the cusp of actually measuring the magnetic field distributions in extragalactic sources through the study of Inverse Compton emission as suggested by Harris & Grindlay (1979). Early results on Centaurus B by Tashiro et al. (1997) and on 3C219 by Brunetti et al. (1999) suggest that variations in the relativistic electron density (relative to the magnetic field energy) may need to vary by factors of $2 - 3$ to explain the radio/X-ray ratios. Although these conclusions are not robust at present, they do suggest a possible major flaw in our assumptions of how magnetic fields vary within a source.

**Misleading Clues to Particle Acceleration.** I was shocked, as all observers should be, when I first saw the results of the numerical simulations described in these proceedings by Tregillis et al. (????). They found that there was little correlation between regions of flat spectra and regions of high emissivity. Since this is not what we expect, e.g., because we expect shocks to be bright and to accelerate particles to flatter spectra, and not what we observe, which is the almost universal correlation between bright regions and flat spectra, their result deserves some explanation.

The regions of flat spectra in the simulations are those where electrons have passed through shocks. In other words, the spectrum of the particles in a given location is a reflection of the **history** of those particles, not simply the local hydrodynamic conditions at the time of observation. Therefore, it is possible to have regions of flat spectrum with no cospatial shock. Similarly, they find that shocks can be currently small and insignificant in emissivity
but still have produced a distinct downstream trail of flat spectrum particles which may be observed. We must therefore approach the identification of flat spectrum regions and particle acceleration sites with great caution. This also implies that particle acceleration can confuse measurements of radiative loss rates even when no site for the acceleration is visible.

We have the remaining question of why bright regions are always observed to have flatter spectra if this is not seen in the simulations. In the simulations Tregillis et al. (????) have performed so far, radiative losses are not important. Therefore, the spectra are straight at each location, and changes in magnetic field along will not change the observed spectral slope. As discussed above, however, when the electron distribution is already curved, high magnetic fields will produce both high emissivities and flat spectra, independent of any particle acceleration.

Inhomogeneities. Inhomogeneities in the magnetic fields can have important consequences both for the evolution of the relativistic particles and for how they appear in observations. On the physical side, (Eilek, Melrose & Walker 1997) and (Tribble Preprint) have discussed the evolution of electron populations when there is diffusion between regions of different magnetic field strengths. The spectra can behave much differently than the standard homogeneous models, and ageing calculations in some circumstances can be completely misleading.

On the observational side, we have shown through the use of spectral tomography (e.g., Katz-Stone & Rudnick (1997), Katz-Stone et al. (1999), Rudnick (1996)) that many sources have overlapping structures of different spectral indices. Figure 1 shows one example. When these overlapping structures are blended and spectral variations are measured along a source, ageing calculations are meaningless. Using tomography or another method prior to ageing analysis should be *de riguer*.

When there is insufficient resolution to detect blends, or the blending of components occurs primarily along the line of sight, the shape of the spectra can still be used to assess its importance. Despite numerous claims to the contrary in the literature, we have yet to find a single source where the spectra are well-fit by any of the standard ageing models. Although data at a given position may appear consistent with one model, nearby positions would yield an apparently different low frequency index, or a different shape, etc. All of this can be assessed using color-color diagrams, as introduced by Katz-Stone, Rudnick, & Anderson (1993). Figure 2 shows how color-color diagrams are constructed and used, and how the two tails of 3C465, e.g., have quite different shapes. These differences are probably a result of either superposition or diffusion effects. Young et al. (????) show results on other WATs. In such cases, ageing calculations can only be performed after the confusing effects
Fig. 1. Two frames from the spectral tomography gallery between $\lambda 6\text{ cm}$ and $\lambda 20\text{ cm}$ for 3C449 (Katz-Stone & Rudnick, 1997). On the left(right) we have isolated the steeper(flatter) spectrum material. Where the flat jet is often mistakenly thought to flare, we see that a new steep spectrum component appears. Spectra that blend these two structures are not appropriate for ageing calculations.

have been removed; this is currently beyond our capability in most cases.

4 Closing Remarks and Recommendations

At this meeting, there was extensive discussion about how pernicious selection effects can be in radio source population studies. Similar problems can lead to spurious correlations between radiative age estimates and other derived source properties such as jet power or dynamical ages. *Caveat Emptor.*

What should we do in the face of all these serious questions about the validity of radiative ages? I feel that two approaches are important.

- *Don’t ignore the discrepancies*—when the spectra do not steepen monotonically, when the low frequency index appears to change throughout a source, when the standard spectral shapes don’t fit.
- *Evaluate alternative histories carefully.* This means that in each source we need to specifically ask what evidence or limits can be placed on a) spectral
Fig. 2. Color-color diagrams. On the left are two illustrations of how spectra in normal \([\log I, \log \nu]\) space translate into color-color space. Left cartoon: different power laws. Right cartoon: the same curved spectrum at each location, but shifted in frequency as would appear under magnetic field changes or ageing. On the right is the color-color diagram along the two tails of 3C465 from the data of Feretti et al., (1998). The best standard spectral shape, a KP spectrum, is shown as a broken line. No standard shapes fit and the meaning of any ageing analyses is unclear.

variations due to magnetic field and/or adiabatic changes, b) \textit{in situ} particle acceleration, and c) confusion between overlapping particle populations.

In summary, it is not sufficient to perform a standard radiative loss analysis and assume that you have learned anything about the age of a source.

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Q: (Peter Barthel) Which age estimates do you trust? Don’t we agree that size/0.1c and spectral ages are in the same ballpark?
A: Yes, but the agreement between these two numbers is not meaningful to me. There are many subtle selection effects that can give spurious correlations. Measured advance speeds, as discussed at this meeting by Conway, probably give reliable order of magnitude ages for at least the CSS sources.

Q: (Dan Harris) I don’t think you should use current claims of IC/3K X-ray emission as evidence for relativistic electron populations in extremely low fields. Therefore, I question your claim of “field not tracking particles.”
A: I agree that the current observations are not conclusive. However, the most straightforward interpretation of the data is that the ratio of relativistic particle/field energies is not constant. This says we need to take this issue seriously.