The inverse-Compton ghost HDF 130 and the giant radio galaxy 6C 0905+3955: matching an analytic model for double radio source evolution

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ABSTRACT
We present new GMRT observations of HDF 130, an inverse-Compton (IC) ghost of a giant radio source that is no longer being powered by jets. We compare the properties of HDF 130 with the new and important constraint of the upper limit of the radio flux density at 240 MHz to an analytic model. We learn what values of physical parameters in the model for the dynamics and evolution of the radio luminosity and X-ray luminosity (due to IC scattering of the cosmic microwave background (CMB)) of a Fanaroff-Riley II (FR II) source are able to describe a source with features (lobe length, axial ratio, X-ray luminosity, photon index and upper limit of radio luminosity) similar to the observations. HDF 130 is found to agree with the interpretation that it is an IC ghost of a powerful double-lobed radio source, and we are observing it at least a few Myr after jet activity (which lasted 5–100 Myr) has ceased. The minimum Lorentz factor of injected particles into the lobes from the hotspot is preferred to be \( \gamma \sim 10^3 \) for the model to describe the observed quantities well, assuming that the magnetic energy density, electron energy density, and lobe pressure at time of injection into the lobe are linked by constant factors according to a minimum energy argument, so that the minimum Lorentz factor is constrained by the lobe pressure. We also apply the model to match the features of 6C 0905+3955, a classical double FR II galaxy thought to have a low-energy cutoff of \( \gamma \sim 10^4 \) in the hotspot due to a lack of hotspot inverse-Compton X-ray emission. The models suggest that the low-energy cutoff in the hotspots of 6C 0905+3955 is \( \gamma \gtrsim 10^3 \), just slightly above the particles required for X-ray emission.

Key words: galaxies: individual: RG J123617/HDF 130, 6C 0905+3955 – galaxies: evolution – galaxies: jets – radio continuum: galaxies – X-rays: galaxies.

1 INTRODUCTION
In this work we establish whether a consistent interpretation can be found for the currently observed properties of the double-lobed sources HDF 130 and 6C 0905+39, the former of which is thought to no longer have current jet activity. We identify at which stage in their life cycles HDF 130 and 6C 0905+3955 could be by comparing their observable features (lobe length, axial ratio, X-ray luminosity, photon index, radio flux density limit) to an analytic model for the dynamics and evolution of X-ray and radio emission of an active FR II object whose jets switch off after a time \( t_j \) developed.

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2 OBSERVATIONS OF HDF 130 AND 6C 0905+39, AND THE MODEL FOR EVOLUTION OF AN FR II OBJECT

2.1 GMRT observations of HDF 130

We observed the target HDF 130 for 9 hours on 2008 Oct 25 using the Giant Metre-wave Radio Telescope (GMRT) at 240 MHz. The observation was made in spectral line mode and had a total bandwidth of 8 MHz, consisting of 128 channels each of 62.5 KHz, for each of RR and LL polarisations, which facilitated both high-fidelity imaging across the primary beam and also efficacious excision of radio-frequency interference. Absolute amplitudes were set using observations of 3C 286. Observations of 1252565, our chosen phase calibrator, were interleaved throughout the observation. After allowing for observations of the calibrator sources, the total on-target time was 7.3 hours giving good UV-coverage to facilitate deconvolution. These data were reduced using standard wide-field procedures within AIPS, including faceting across the full primary beam. The innermost region of the resultant image is shown in Figure 1 which has resolution of 17 arcsec by 14 arcsec. The upper limit of the radio flux density of HDF 130 at 240 MHz in an 81 arcsec by 15 arcsec area centered on the source is 11 mJy. The 3σ flux density upper limit is 33 mJy.

2.2 Previous HDF 130 observations

HDF 130 was most recently analysed in the X-ray by Fabian et al. (2009), who is a source of (∼5×10^11 M⊙, stellar population) Case et al. (2009) elliptical galaxy at z = 1.99 with a roughly double-lobed structure in the X-ray and a compact radio nucleus. Each lobe is approximately 0.54 kpc long with an axial ratio (single lobe length divided by width of the lobe) of 2 (Fabian et al. 2009). The X-ray image of HDF 130 observed in the Chandra Deep Field-North 2 Ms exposure was best modelled with a photon index of Γ = 2.65 by Fabian et al. (2009) and has a 2–10 keV luminosity of 5.4 × 10^40 erg s^-1.

2.3 Previous 6C 0905+3955 observations

The powerful z = 1.88 FR II source 6C 0905+3955 was most recently observed in the X-ray by XMM-Newton (Erlund et al. 2008). The source is a massive (9.45 kpc (Blundell et al. 2006) with an axial ratio of 8, although the source has arm-length asymmetry (the ratio of arm lengths is 1.6) (Law-Green et al. 1995, Erlund et al. 2008). The extended X-ray lobe emission was modelled with a photon index of Γ = 1.61 and has a 2–10 keV luminosity of 1.5 × 10^44 erg s^-1 (Erlund et al. 2008). The MERLIN 408 MHz image gives a radio luminosity of the lobes of 8.4 × 10^45 erg s^-1 (Law-Green et al. 1995).

2.4 Model for evolution of a double radio source

We use a model for evolution of double radio sources developed in Mocz et al. (2011), where the details may be found, in order to determine the source properties of HDF 130 and 6C 0905+3955 and their evolutionary stage at the time of observation. Here we outline some of the basic features of the model. The model is an analytic one for the dynamics and evolution of the radio luminosity and X-ray luminosity (due to IC scattering of the CMB) of FR II radio galaxies. It accounts for injection of relativistic particles into the lobes of radio galaxies, and for adiabatic, synchrotron and IC energy losses to describe the evolution of the emission in the radio and the X-ray bands assuming a powerful double-lobed radio galaxy whose jets turn off after a typical jet lifetime. The model is based on the formalisms of Kaiser et al. (1997), Kaiser & Alexander (1997), Blundell et al. (1999) and Nath (2010).

The model is characterized by the jet power Q_j (per jet), jet lifetime t_j, ambient density described by

\[ \rho(r) = \rho_0(r/a_0)^{-\beta} \]

and a power-law injection spectrum into the lobe of

\[ n(\gamma, t_j) d\gamma_j = n_0 \gamma_j^{-\beta} d\gamma_j \]

with \( \gamma_j \) between \( \gamma_{\text{min}} \) and \( \gamma_{\text{max}} \).

In the model, we have injection of relativistic electrons into the expanding lobe until jet activity stops and no further particles are added into the lobe. The energy loss equation describes the time evolution of the Lorentz factors of the electrons:

\[ \frac{d\gamma}{dt} = -\frac{1}{3} \frac{dV_l}{dt} \frac{4 \sigma_T}{3 mc^2} \left( u_B + u_e \right) \gamma^2 \]

where the first term is the energy loss due to the adiabatic expansion of the lobe of volume \( V_l \) and the second term describes the synchrotron and IC losses. Here \( m_e \) is the mass of an electron, \( u_e = a(2.7 K (1+z))^4 \) is the CMB photon energy density at the redshift of the source and \( a = 7.565 \times 10^{-16} \) K \( \text{J}^{-1} \text{m}^{-3} \).
The pressure in the lobes, the energy density of the electrons, and the energy density of the magnetic field in the model are related by constants of order unity based on minimum energy arguments, adapted from Kaiser et al. (1997). The strength of the magnetic field is governed by the jet power (higher jet power corresponding to higher magnetic fields), and the magnetic fields do decrease in the evolution of the source as the lobes expand. The magnetic fields range between 0.1–10 µG.

Typical jet energies may range from $5 \times 10^{37}$ W to $10^{40}$ W, and jet lifetimes may vary from $10^6$ yr to $10^9$ yr. More powerful
jets give rise to lobes that are brighter and grow larger. During the
time the jet is on, the radio luminosity decreases with time but the
X-ray luminosity increases because higher energy electrons, losing
their energy more quickly, downshift to Lorentz factors of
\( \gamma \sim 10^3 \) needed for the IC scattering of CMB photons to 1 keV energies
and the injection of new energetic electrons into the lobe by the jet
more than compensates for the original \( \gamma \sim 10^4 \) electrons losing
energy. Once the jet is off, there is no injection of new particles and
the radio and X-ray luminosities fall (the fall is faster in the radio
as higher energy electrons required for synchrotron radiation lose
energy more rapidly).

One set of environmental parameters inferred from observations
is: \( \beta = 1.5 \), \( \alpha_0 = 10 \) kpc and \( \rho_0 = 1.67 \times 10^{-23} \) kg m\(^{-3}\)
(Blundell et al. 1999). A less dense environment would allow for
sources to grow larger but luminosity then falls more quickly due
to increased adiabatic losses. The injection index \( p \) is between 2
and 3 (Alexander & Leahy 1987). The maximum injected Lorentz
factor \( \gamma_{\text{max}} \) is set to 105 as Lorentz factors of \( \gamma \sim 10^3 \) are required
to produce upscattering of the CMB in the X-ray and Lorentz
factors of \( \gamma \geq 10^2 \) are needed for GHz synchrotron radiation in
the radio for typical magnetic field strengths of \( B \sim 0.1\)–10 \( \mu \)G.
The minimum injected Lorentz factor \( \gamma_{\text{min}} \) may in principle be as low
as 1.

The output luminosities of the model are in units of power per
frequency per steradian, which is converted to a power (units of
\( \text{erg s}^{-1} \)) by multiplying by \( 4\pi \) steradians and the frequency \( \nu \) of
the emission.

3 RESULTS

Our physical model for the radio source has 8 parameters (jet ener-
ity, jet lifetime, minimum injected Lorentz factor \( \gamma_{\text{min}} \), injection
power spectrum index \( p \), \( \beta \) and \( \rho_0 \) characterizing the environment,
and the time of observation). We have five predicted observables
(lobe length, axial ratio, X-ray luminosity, photon index, radio flux
density limit). Therefore we cannot fit the model to the 5 data points
since we would be overfitting. However, we can do something sim-
ple. We can consider a wide range of parameters which observa-
tions suggest describe most double-lobed radio sources and test
which combinations of parameters can yield an object that is simi-
lar to HDF 130 or 6C 0905+3955. Looking at the sets of parameters
that do well will indicate what types of scenarios may be possible.
We are not able to conclude the value of any physical parameter
specifically but can learn that certain values for a specific parameter
in the model may be unable to reproduce observed source proper-
ties. The length of time of the observational window during which
a specific set of physical parameters leads to a model similar to the
observed source gives an estimate of the likelihood of the model.
Without considering the observational window, all the sets of pa-
rameters that describe a source similar to the observed properties
are equally likely candidates to describe the source. But considering
the observational window, a model that describes a source with
similar features to the observed source for only a very brief period
of time is less probable to be the correct descriptor than a model
that does so for a longer window. In order to estimate whether
one value, \( x_1 \) for a parameter \( x \) may be preferred over another, \( x_2 \),
in a Bayesian sense, one may compare the total length of time of
the congruent observational windows of all the models investigated
with \( x = x_1 \) to all the models with \( x = x_2 \).

The source parameters being fit are obtained from the obser-
vations mentioned in §2. We list the parameters here: HDF 130
has lobe of length 345 kpc, axial ratio 2.0, 1 keV X-ray luminos-
ity of \( 8.5 \times 10^{43} \) erg s\(^{-1} \), \( \Gamma = 2.65 \) and upper limit of the radio
luminosity at 240 MHz of \( 2.3 \times 10^{42} \) erg s\(^{-1} \). 6C 0905+3955 has
lobe of length 472 kpc, axial ratio 8.0, 1 keV X-ray luminosity of
\( 22.3 \times 10^{43} \) erg s\(^{-1} \), \( \Gamma = 1.61 \) and radio luminosity at 408 MHz
of \( 83.5 \times 10^{42} \) erg s\(^{-1} \).

We consider a range of parameters and test which models (at
some point in their evolution, the congruent observational window,
denoted by \( t_{\text{lobe}} \)) give a lobe length, axial ratio, X-ray luminosity
and photon index that agree with HDF 130 to within 30 per cent as
well as a 240 MHz radio luminosity that is below the 3\( \sigma \) flux density
limit (this percentage is arbitrary but was chosen to be large
to search for sets of parameters that model sources similar to the
observations without having to narrow down any parameter too
precisely). We also test which models agree with 6C 0905+3955
to within 60 per cent (a higher margin of error is considered for
this source as it is asymmetric which our model does not ac-
count for). We look at jet energies ranging from \( 5 \times 10^{37} \) W to
\( 10^{38} \) W; jet lifetimes from \( 10^3 \) years to \( 10^5 \) years, \( \beta = 1.5 \) and
2, \( \rho_0 = 1.67 \times 10^{-23} \) kg m\(^{-3} \), \( \gamma_{\text{min}} \) of 1, \( 10^3 \) and \( 10^4 \),
and injection indices of 2.14, 2.5 and 3. The parameters considered
are listed in Table 1. A total of 2304 models were tested by consid-
ering all combinations of the parameters in Table 1. Of these 2304
runs, 19 end up closely resembling all five of the observational fea-
tures of HDF 130 at some point in the evolution of the source. These
models are presented in Table 2. The models that closely describe
6C 0905+3955 are presented in Table 3. The predicted observable
features of the congruent models are presented in Tables A1 and
A2 of the Appendix, and are compared to the observed values. Fig-
ure 2 shows an example (model [14] for HDF 130) of how X-ray
luminosities and radio luminosities are predicted by the model to
evolve with time.

We may obtain a constraint on \( p \) from \( \Gamma \) for an active source.
The value of \( p \) is probably steeper than the value implied by \( \Gamma \)
(namely, \( p = 2\Gamma - 1 \)) to reflect the empirical point that for an
active classical double radio source the spectrum has a gradient
flatter at lower \( \gamma \) (which may reflect a cutoff/turnover/\( \gamma_{\text{min}} \)) and not
representative of the high \( \gamma \) particles responsible for GHz emission.
Table 3 for the source 6C 0905+3955 shows the values of \( p \) greater
than the value implied by \( \Gamma \) in bold. For a source that has turned
off, such as HDF 130, the observed \( \Gamma \) grows with time regardless of
the value of \( p \) for the injection spectrum, so we cannot make such a
constraint.

The models that do reasonably well at describing a source simi-
lar to HDF 130 all suggest that the source is being viewed after the
jets have turned off (by at least 5 Myr) while the radio lobe emis-
sion is falling rapidly or has already dropped to below telescope
sensitivity. All models except one (which has a short observational
window) require \( \gamma_{\text{min}} \) to be 1000 rather than 1. With \( \gamma_{\text{min}} = 1 \) the
FR II object in the models are not bright enough in the X-rays (see
§5.1 for a discussion on the effects of varying \( \gamma_{\text{min}} \)) during the

3 RESULTS

| Parameter | values |
|-----------|--------|
| \( Q_1 \) (W) | \( 5 \times 10^{37}, 10^{38}, 2 \times 10^{38}, 5 \times 10^{38}, \ldots, 10^{40} \) |
| \( t_j \) (yr) | \( 10^5, 5 \times 10^5, 10^6, 5 \times 10^6, \ldots, 10^9 \) |
| \( \beta \) | 1.5, 2 |
| \( \rho_0 \) (kg m\(^{-3} \)) | \( 1.67 \times 10^{-23}, 1.67 \times 10^{-22} \) |
| \( \gamma_{\text{min}} \) | 1, 10^3, 10^4 |
| \( p \) | 2.14, 2.5, 3 |
times when the other parameters (length, photon index, etc.) agree

\[ a \times 10^{38} \text{ W} \quad \text{b (Myr)} \quad \text{c (x} 10^{-23} \text{ kg m}^{-3} \text{)} \]

\[ d \times (t_j) \]

\[ \begin{array}{cccccccc}
  \# & Q^a & t_b^b & \gamma_{\text{min}} & p & \beta & \rho_0^c & t_{\text{obs}}^d \\
  [1] & 1 & 100 & 1000 & 3 & 1.5 & 16.7 & 1.07 \text{ to } 1.11 \\
  [2] & 2 & 100 & 1000 & 3 & 2 & 16.7 & 1.05 \text{ to } 1.11 \\
  [3] & 5 & 50 & 1000 & 2.5 & 1.5 & 1.67 & 1.13 \text{ to } 1.29 \\
  [4] & 5 & 50 & 1000 & 2.5 & 1.5 & 16.7 & 1.16 \text{ to } 1.27 \\
  [5] & 5 & 50 & 1000 & 3 & 1.5 & 1.67 & 1.11 \text{ to } 1.31 \\
  [6] & 5 & 50 & 1000 & 3 & 2 & 16.7 & 1.18 \text{ to } 1.27 \\
  [7] & 5 & 100 & 1000 & 2.14 & 1.5 & 16.7 & 1.09 \text{ to } 1.11 \\
  [8] & 5 & 100 & 1000 & 2.5 & 1.5 & 16.7 & 1.10 \text{ to } 1.15 \\
  [9] & 10 & 50 & 1000 & 2.14 & 1.5 & 16.7 & 1.16 \text{ to } 1.20 \\
  [10] & 10 & 50 & 1000 & 2.14 & 2 & 16.7 & 1.17 \text{ to } 1.31 \\
  [11] & 10 & 50 & 1000 & 2.5 & 1.5 & 16.7 & 1.16 \text{ to } 1.20 \\
  [12] & 10 & 50 & 1000 & 2.5 & 2 & 16.7 & 1.25 \text{ to } 1.33 \\
  [13] & 10 & 100 & 1000 & 2.14 & 1.5 & 16.7 & 1.10 \text{ to } 1.13 \\
  [14] & 20 & 10 & 1000 & 2.5 & 2 & 1.67 & 1.70 \text{ to } 1.95 \\
  [15] & 20 & 10 & 1000 & 3 & 2 & 1.67 & 1.68 \text{ to } 2.04 \\
  [16] & 20 & 50 & 1000 & 2.14 & 1.5 & 16.7 & 1.18 \text{ to } 1.22 \\
  [17] & 50 & 50 & 1 & 2.14 & 1.5 & 16.7 & 1.15 \text{ to } 1.18 \\
  [18] & 100 & 5 & 1000 & 2.14 & 2 & 1.67 & 2.45 \text{ to } 2.53 \\
  [19] & 100 & 5 & 1000 & 2.5 & 2 & 1.67 & 2.45 \text{ to } 2.49 \\
\end{array}\]

Table 3. Models that agree with 6C 0905+3955 observations

\[ a \times 10^{38} \text{ W} \quad \text{b (x} 10^{-23} \text{ kg m}^{-3} \text{)} \quad \text{c (x} 100 \text{ Myr) } \]

\[ \begin{array}{cccccccc}
  \# & Q^a & \gamma_{\text{min}} & p & \beta & \rho_0^c & t_{\text{obs}}^d \\
  [1] & 50 & 1 & 2.14 & 1.5 & 1.67 & 0.42 \text{ to } 0.52 \\
  [2] & 50 & 1 & 2.14 & 2 & 1.67 & 0.54 \text{ to } 0.60 \\
  [3] & 50 & 1000 & 2.14 & 1.5 & 1.67 & 0.45 \text{ to } 0.52 \\
  [4] & 50 & 1000 & 2.14 & 2 & 1.67 & 0.21 \text{ to } 0.28 \\
  [5] & 50 & 1000 & 2.5 & 2 & 1.67 & 0.17 \text{ to } 0.28 \\
  [6] & 50 & 1000 & 3 & 2 & 1.67 & 0.17 \text{ to } 0.28 \\
  [7] & 100 & 1 & 2.14 & 1.5 & 1.67 & 0.30 \text{ to } 0.41 \\
  [8] & 100 & 1 & 2.14 & 2 & 1.67 & 0.21 \text{ to } 0.22 \\
  [9] & 100 & 1 & 2.14 & 2 & 1.67 & 0.42 \text{ to } 0.47 \\
  [10] & 100 & 1000 & 2.14 & 2 & 1.67 & 0.21 \text{ to } 0.22 \\
\end{array}\]

3.1 The effects of $\gamma_{\text{min}}$

The question arises why changing $\gamma_{\text{min}}$ has an effect on the evolution of the source because the electrons below $\gamma_{\text{min}}$ do not contribute to the 1keV X-ray and 151MHz radio emission. In short, increasing $\gamma_{\text{min}}$ only from a set of given parameters will drive the source to become brighter without changing lobe growth because the electron energy density of the injection spectrum in our model stays the same as it is assumed to be linked by a minimum energy argument, to the source pressure by a constant factor, and the pressure is determined by the jet power and the environmental parameters. Having the injected particle energy density constant but increasing $\gamma_{\text{min}}$ yields more high $\gamma$ particles (see the two solid color injection spectra in Figure [3]) and hence a brighter source at 1keV and 151MHz. Alternatively, we can ask ourselves what is the effect of extending the electron energy spectrum below $\gamma_{\text{min}}$ without keeping electron energy density constant. If we assume an injected electron spectrum with high $\gamma_{\text{min}}$ and then extrapolate the spectrum to include lower $\gamma$ particles (see the dashed injection spectra in Figure [3]) then this will increase the energy density of electrons, hence the pressure and the dynamics of the source are altered and the lobes grow much larger. The combination of lobe size and source brightness will constrain possible values of $\gamma_{\text{min}}$ in our sources.

4 DISCUSSION AND CONCLUSION

We matched the observational features of HDF 130 and 6C 0905+3955 to analytic models of the evolution of the lobe size, axial ratio, photon index, and X-ray and radio luminosities of an FR II object. Only periods of time when the source is no longer active in the models are congruent to the observations of HDF 130, supporting the idea that HDF 130 is an IC ghost of a giant radio source. The models suggest HDF 130 experienced jet activity for a period of around 5–100 Myr, and that we are viewing

![Figure 2. Evolution of X-ray and radio luminosities of model [14] for HDF 130 after jet activity has halted. The solid track shows the 1 keV X-ray power. The dashed/dot-dashed/dotted blue lines show the evolution of the 240/151/74 MHz luminosities. Vertical dashed lines show the duration in the evolution of the source that is similar to HDF 130. The horizontal thin dashed lines show the ±30 per cent range of acceptable X-ray luminosities and the 3σ 240 MHz luminosity upper limit of emission.](image-url)
the object at least a few Myr after the jets have turned off, which is why the source is not bright in the radio. 6C 0905+3955 is inferred to have had an active jet for at least 20 Myr and may have a slightly higher intrinsic jet power than HDF 130.

Predicted radio luminosities at lower frequencies (151 and 74 MHz) for the models that agree with HDF 130 are included in Table 4. Even at 151 MHz the ghost source may not be observable. However, the models predict that the source will be observable in the 74 MHz band, with luminosity on the order of $10^{23}$ erg s$^{-1}$, or, equivalently, $10^{20}$ W Hz$^{-1}$ sr$^{-1}$. New low-frequency observations of HDF 130 could test this.

Some models predict the lobe lengths in the lower limit of the error tolerance during the observational congruent window of HDF 130, while predicting the other features accurately. If such is the case, perhaps the surrounding density profile is not as simple as we have assumed it to be and allows for the lobes to grow larger than in our models while staying bright in the X-ray. It is plausible that the source is expanding into a pre-existing lobe from a previous episode of jet activity, which cleared away some of the surrounding material and would mean expansion losses are smaller and the lobes can grow larger and brighter.

Importantly, the minimum Lorentz factor of injected particles into the lobe for HDF 130 is found to be on the order of $\gamma_{\text{min}} = 1000$ rather than $\gamma_{\text{min}} = 1$. Even a $\gamma_{\text{min}} = 30$ or $\gamma_{\text{min}} = 100$ is not preferred by HDF 130: repeating fitting the observable properties of HDF 130 with models that have $\gamma_{\text{min}} = 30$ and $\gamma_{\text{min}} = 100$ gives only 4 congruent models observational windows of at most 3 Myr, reported in Table 4.

In the model, a higher $\gamma_{\text{min}}$ (while keeping injected electron energy density constant) will produce brighter sources without affecting the lobe growth, which is determined by the jet power and the surrounding density profile. Increasing the jet power makes the jet grow larger and brighter. It is the combination of HDF 130 lobe size, which is not exceptionally large, and X-ray brightness which forces the model to require $\gamma_{\text{min}} \sim 1000$ to agree with the observational features.

The minimum injected Lorentz factor for 6C 0905+3955 is also found to be most likely on the order of $\gamma_{\text{min}} = 1000$ (or also marginally 1), based on only best matching the total lobe luminosities predicted by the model to the observed luminosities. Considering only the models where $p$ is steeper than implied by $\Gamma$ (these values are bold in Table 3), we see that only $\gamma_{\text{min}} = 1000$ is preferred. In previous observations, no X-ray emission is seen in a hotspot of 6C 0905+3955 (other than highly energetic X-ray synchrotron requiring extremely high Lorentz factors Erlund et al. (2008)) which suggests that there is a low-energy cutoff of the freshly injected particles into the lobe above the $\sim 10^3$ particles required for X-ray emission from upscattering on the CMB. Likely, the minimum energy cutoff is just above the critical Lorentz factor which would result in X-ray emission from the hotspot. It is important to note that 6C 0905+3955 may be more complicated than described by our simple model, because 6C 0905+3955 is asymmetric, probably due to an asymmetric surrounding environment. There may also be complex mechanisms happening in the lobes, such as reflected shocks or interruptions of the jet at the hotspot (Law-Green et al. 1995), which are so far unaccounted for by our model.

The chosen value of $\gamma_{\text{min}}$ varies by orders of magnitude in previous papers, as it often has to be estimated. The minimum Lorentz factor is assumed to be typically 1 in previous models of FR II evolution by Kaiser et al. (1997), Kaiser & Alexander (1997), Blundell et al. (1999) and Nath (2010), Croston et al. (2005) use a value of 10, Carilli et al. (1991) use a value of 100, and Wardle et al. (1998) use a value of 1000. If HDF 130 and 6C 0905+3955 are typical sources, it may be the case that the minimum energy of particles injected into the lobes is large. The value of $\gamma_{\text{min}}$ may at first appear as an eclectic, unimportant detail, but Mocz et al. (2011) show that the typical value of $\gamma_{\text{min}}$ can significantly affect estimates for the total population of FR II sources from a radio luminosity function as it changes the time sources fall below a given flux limit in their evolution. A higher $\gamma_{\text{min}}$ will also increase the detectability of IC ghosts.

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APPENDIX A: MODEL PREDICTIONS

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Table A1. Model predictions during congruent observational window compared to HDF 130 observations

| #  | lobe length $^a$ | axial ratio | $L_{\text{r,1keV}}^b$ | $\Gamma$ | $L_{\text{r,240MHz}}^c$ | $L_{\text{r,151MHz}}^d$ | $L_{\text{r,74MHz}}^e$ |
|----|----------------|------------|-----------------|--------|----------------|----------------|----------------|
| obs. | 345 | 2.0 | 8.5 | 2.65 | < 2.3 | (0.05 to 0.05) | (0.08 to 0.03) | (0.03 to 0.18) | (1.62 to 0.02) |
| [1] | 278 to 281 | 2.1 to 2.1 | 7.8 to 6.2 | 2.6 to 3.1 | 1.3 to 0 | 3.8 to 0.1 | 10.5 to 3.5 |
| (−0.2 to −0.19)$^f$ | (0.05 to 0.29) | (−0.27 to −0.28) | (−0.03 to 0.09) | (0.63 to 0) |
| [2] | 435 to 444 | 2.5 to 2.5 | 6.2 to 6.1 | 2.0 to 2.9 | 0.5 to 0 | 1.0 to 0 | 2.3 to 0.3 |
| (0.26 to 0.29) | (0.25 to 0.25) | (−0.27 to −0.28) | (−0.25 to 0.09) | (0.63 to 0.0) |
| [3] | 391 to 408 | 2.6 to 2.6 | 7.8 to 6.0 | 1.9 to 2.7 | 1.8 to 0 | 3.8 to 0 | 7.1 to 0.1 |
| (0.13 to 0.18) | (0.3 to 0.3) | (−0.08 to −0.29) | (−0.27 to 0.03) | (2.32 to 0.0) |
| [4] | 390 to 317 | 2.4 to 2.4 | 8.7 to 5.9 | 2.3 to 2.8 | 1.5 to 0 | 5.8 to 0 | 13.3 to 2.0 |
| (−0.11 to −0.08) | (0.18 to 0.18) | (0.03 to 0.03) | (−0.12 to 0.07) | (1.89 to 0) |
| [5] | 389 to 410 | 2.6 to 2.6 | 10.7 to 6.5 | 2.0 to 3.4 | 1.7 to 0 | 3.7 to 0 | 8.0 to 0 |
| (0.13 to 0.19) | (0.3 to 0.3) | (0.26 to 0.23) | (−0.24 to 0.29) | (2.25 to 0) |
| [6] | 308 to 317 | 2.4 to 2.4 | 10.9 to 6.8 | 2.8 to 3.4 | 0 to 0 | 1.6 to 0 | 9.0 to 0.9 |
| (−0.11 to −0.08) | (0.18 to 0.18) | (0.28 to −0.2) | (0.07 to 0.29) | (0.01 to 0) |
| [7] | 363 to 365 | 2.3 to 2.3 | 6.8 to 6.1 | 2.2 to 2.4 | 1.0 to 0 | 6.8 to 1.6 | 14.2 to 10.0 |
| (0.05 to 0.06) | (0.16 to 0.16) | (−0.2 to −0.28) | (−0.15 to −0.11) | (1.3 to 0) |
| [8] | 364 to 369 | 2.3 to 2.3 | 10.3 to 6.9 | 2.6 to 3.3 | 0 to 0 | 2.9 to 0 | 13.9 to 1.7 |
| (0.05 to 0.07) | (0.16 to 0.16) | (0.21 to −0.19) | (−0.01 to 0.23) | (0 to 0) |
| [9] | 249 to 252 | 2.2 to 2.2 | 7.3 to 6.1 | 2.4 to 2.8 | 0.4 to 0 | 24.4 to 0.7 | 54.2 to 34.6 |
| (−0.28 to −0.27) | (0.09 to 0.09) | (−0.13 to −0.28) | (−0.09 to 0.04) | (0.56 to 0.0) |
| [10] | 387 to 404 | 2.6 to 2.6 | 8.6 to 6.0 | 2.1 to 2.7 | 2.0 to 0 | 9.0 to 0 | 16.9 to 0.3 |
| (0.12 to 0.17) | (0.29 to 0.29) | (0.01 to −0.29) | (−0.22 to 0) | (2.6 to 0) |
| [11] | 249 to 252 | 2.2 to 2.2 | 10.9 to 8.3 | 2.8 to 3.3 | 0 to 0 | 19.3 to 0 | 68.2 to 36.7 |
| (−0.28 to −0.27) | (0.09 to 0.09) | (0.28 to −0.02) | (0.07 to 0.26) | (0 to 0) |
| [12] | 397 to 406 | 2.6 to 2.6 | 10.8 to 7.6 | 2.7 to 3.4 | 0 to 0 | 0 to 0 | 5.8 to 0 |
| (0.15 to 0.18) | (0.29 to 0.29) | (0.27 to −0.1) | (0.02 to 0.28) | (0 to 0) |
| [13] | 444 to 447 | 2.5 to 2.5 | 10.8 to 9.1 | 2.3 to 2.6 | 0 to 0 | 7.6 to 0 | 22.4 to 11.2 |
| (0.29 to 0.3) | (0.25 to 0.25) | (0.27 to 0.07) | (−0.13 to −0.03) | (0 to 0) |
| [14] | 243 to 257 | 2.5 to 2.5 | 7.4 to 6.0 | 2.1 to 2.4 | 2.2 to 0 | 10.7 to 0 | 21.6 to 8.2 |
| (−0.3 to −0.26) | (0.25 to 0.25) | (−0.12 to −0.3) | (−0.19 to −0.11) | (2.84 to 0) |
| [15] | 242 to 262 | 2.5 to 2.5 | 9.9 to 6.0 | 2.6 to 3.1 | 0.9 to 0 | 6.6 to 0 | 20.1 to 2.4 |
| (−0.3 to −0.24) | (0.25 to 0.25) | (0.16 to −0.3) | (−0.03 to 0.17) | (1.19 to 0) |
| [16] | 305 to 309 | 2.3 to 2.3 | 10.7 to 8.5 | 2.7 to 3.3 | 0 to 0 | 16.1 to 0 | 76.6 to 41.9 |
| (−0.12 to −0.11) | (0.17 to 0.17) | (0.26 to 0) | (0 to 0.23) | (0 to 0) |
| [17] | 393 to 397 | 2.6 to 2.6 | 7.3 to 6.2 | 2.5 to 2.8 | 0.5 to 0 | 31.6 to 6.2 | 70.4 to 50.1 |
| (0.14 to 0.15) | (0.3 to 0.3) | (−0.14 to −0.27) | (−0.05 to 0.07) | (0.68 to 0) |
| [18] | 242 to 245 | 2.6 to 2.6 | 6.3 to 6.0 | 2.5 to 2.7 | 0 to 0 | 0 to 0 | 31.9 to 23.9 |
| (−0.3 to −0.29) | (0.29 to 0.29) | (−0.26 to −0.3) | (−0.04 to 0.02) | (0 to 0) |
| [19] | 242 to 243 | 2.6 to 2.6 | 7.7 to 7.4 | 3.3 to 3.4 | 0 to 0 | 0 to 0 | 25.6 to 20.9 |
| (−0.3 to −0.29) | (0.29 to 0.29) | (−0.09 to −0.13) | (0.25 to 0.29) | (0 to 0) |

$^a$ (kpc)

$^b$ ($\times 10^{41}$ erg s$^{-1}$)

$^c$ ($\times 10^{42}$ erg s$^{-1}$)

$^d$ ($\times 10^{42}$ erg s$^{-1}$)

$^e$ ($\times 10^{42}$ erg s$^{-1}$)

$^f$ fractional deviation

$^g$ fraction of 1σ upper limit
Table A2. Model predictions during congruent observational window compared to 6C 0905+3955 observations

| #    | lobe length $^a$ (kpc) | axial ratio | $L_{\nu,1keV}$ $^b$ (×10^{43} \text{ erg s}^{-1})$ | $\Gamma$ | $L_{\nu,408MHz}$ $^c$ (×10^{42} \text{ erg s}^{-1})$ |
|------|------------------------|------------|---------------------------------|----------|---------------------------------|
| obs. | 472                    | 8.0        | 22.3                            | 1.61     | 83.5                            |
| [1]  | 626 to 752             | 3.2 to 3.3 | 10.2 to 11.2                    | 1.8 to 1.8 | 46.5 to 34.0                   |
| (0.33 to 0.59) | (−0.6 to −0.58)       | (−0.54 to −0.5) | (0.1 to 0.11)                   | (−0.45 to −0.6) |
| [2]  | 675 to 750             | 3.2 to 3.3 | 11.6 to 12.0                    | 1.8 to 1.8 | 50.1 to 41.0                   |
| (0.43 to 0.59) | (−0.6 to −0.59)       | (−0.48 to −0.46) | (0.12 to 0.13)                   | (−0.4 to −0.51) |
| [3]  | 664 to 752             | 3.2 to 3.3 | 19.8 to 21.3                    | 1.0 to 1.1 | 131.1 to 105.7                 |
| (0.41 to 0.59) | (−0.59 to −0.58)      | (−0.11 to −0.04) | (−0.35 to −0.32)           | (0.56 to 0.26)    |
| [4]  | 566 to 754             | 3.4 to 3.6 | 9.0 to 10.7                     | 0.8 to 0.8 | 77.9 to 46.0                   |
| (0.2 to 0.6)  | (−0.58 to −0.55)      | (−0.6 to −0.52) | (−0.53 to −0.48)           | (−0.07 to −0.45) |
| [5]  | 458 to 754             | 3.2 to 3.6 | 14.2 to 19.0                    | 0.7 to 0.9 | 131.0 to 49.8                  |
| (−0.03 to 0.6) | (−0.6 to −0.55)       | (−0.36 to −0.15) | (−0.54 to −0.46)           | (0.56 to −0.41) |
| [6]  | 458 to 754             | 3.2 to 3.6 | 21.0 to 27.7                    | 0.8 to 0.9 | 112.8 to 37.5                  |
| (−0.03 to 0.6) | (−0.6 to −0.55)       | (−0.06 to 0.24) | (−0.52 to −0.44)           | (0.34 to −0.55) |
| [7]  | 572 to 748             | 3.2 to 3.4 | 14.6 to 17.2                    | 1.7 to 1.8 | 132.4 to 89.4                  |
| (0.21 to 0.58) | (−0.6 to −0.57)      | (−0.34 to −0.23) | (0.08 to 0.1)               | (0.58 to 0.06)    |
| [8]  | 713 to 747             | 3.7 to 3.7 | 9. to 9.2                      | 1.6 to 1.6 | 42.2 to 38.9                   |
| (0.51 to 0.58) | (−0.54 to −0.53)      | (−0.6 to −0.59) | (0.02 to 0.02)               | (−0.5 to −0.54) |
| [9]  | 602 to 741             | 3.3 to 3.4 | 17.4 to 18.4                    | 1.8 to 1.8 | 130.7 to 108.2                 |
| (0.4 to 0.57)  | (−0.59 to −0.58)      | (−0.22 to −0.18) | (0.11 to 0.12)           | (0.56 to 0.29)    |
| [10] | 713 to 747             | 3.7 to 3.7 | 15.1 to 15.5                    | 0.8 to 0.8 | 131.1 to 121.                   |
| (0.51 to 0.58) | (−0.54 to −0.53)      | (−0.32 to −0.3) | (−0.53 to −0.52) | (0.56 to 0.44)    |

$^a$ (kpc)

$^b$ (×10^{43} \text{ erg s}^{-1})

$^c$ (×10^{42} \text{ erg s}^{-1})