Polarized synchrotron emission and absorption coefficients for thermal, nonthermal, and kappa electron distributions

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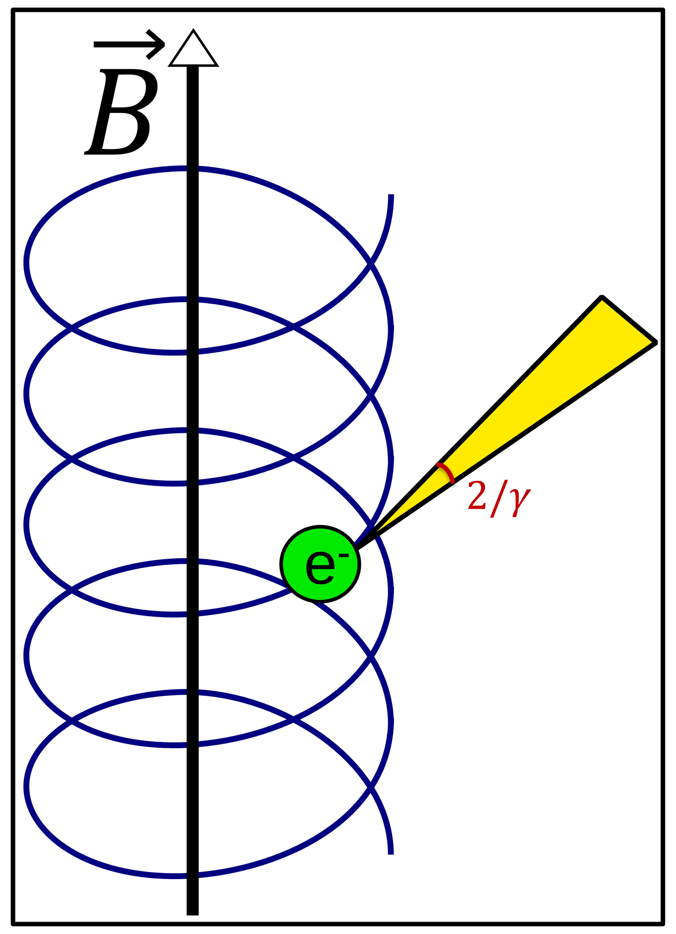
Why study synchrotron?

- Black holes have never been directly imaged
- A global collaboration called the Event Horizon Telescope (EHT) will attempt to image the black hole at the center of the Milky Way (Sgr A*)
    - This is about as difficult as it is to image an orange on the moon *from Earth*
- It will do this using a telescope with an effective size comparable to the *radius of the Earth*
- The EHT will also image the hot plasma orbiting around the hole (the accretion disk)
    - This plasma reaches billions of degrees and emits **synchrotron radiation**
    - The properties of this radiation are dependent on the properties of the disk and the black hole itself
- Our goal is to model synchrotron emission and absorption precisely, so that we can make accurate models of synchrotron-emitting plasmas
- We could then compare these models to EHT images to probe the properties of the black hole and the disk

What is synchrotron radiation?



Schematic illustrating synchrotron radiation production by a relativistic electron (in green) orbiting around a magnetic field line (black). The electron follows a helical orbit (dark blue) and emits radiation into a cone-shaped region (yellow) of width $2/\gamma$ (dark red).

- Synchrotron radiation is ubiquitous in the universe – it arises any time charged particles interact with a magnetic field
- It is a primary mechanism of radiation production for most astronomical plasmas, including:
    - Extragalactic radio jets
    - Planetary magnetospheres
    - **Black hole accretion disks**

Method

Emission and Absorption Coefficients

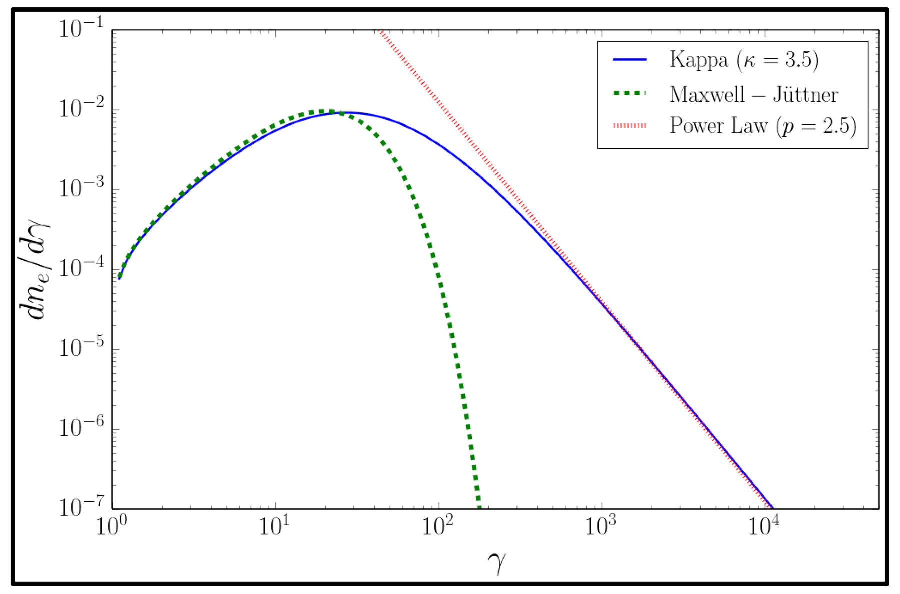
- In order to study the amount of synchrotron radiation produced by a plasma, we first looked at emission and absorption coefficients
    - The emission coefficient j_ν describes the amount of radiation that passes through a region of space
    - The absorption coefficient α_ν describes the amount of radiation that is absorbed by a chunk of matter
- We calculate j_ν and α_ν by evaluating integrals of the following form:

$$j_\nu, \alpha_\nu \propto \int_1^\infty d\gamma \int_{-1}^{1} d\cos(\xi) \sum_{n=1}^{\infty} \delta(y_n)\, I(n, \gamma, \xi)$$

- This has to be done numerically

Code to calculate j_ν and α_ν: `symphony`

- We wrote a fast, full-featured code in `C` called `symphony` in order to calculate j_ν and α_ν
- `symphony` can do these calculations for *polarized* emission and absorption
    - Understanding polarized emission and absorption allows us to better probe the properties of the plasma
    - The EHT can detect polarized radiation from Sgr A*
- `symphony` can also do these calculations for *arbitrary* electron energy distributions
- Three distribution functions were studied explicitly:
    - A relativistic thermal (Maxwell-Jüttner) distribution
    - A nonthermal (power-law) distribution
    - A kappa distribution

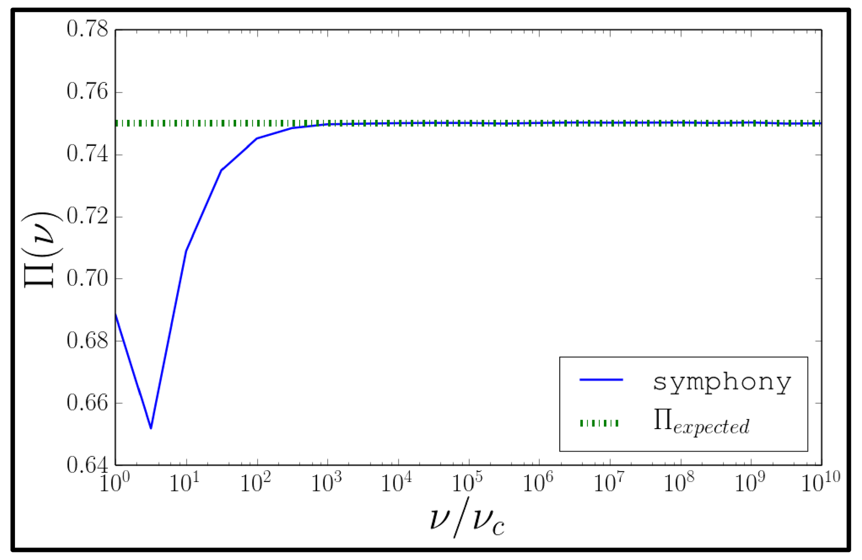


Qualitative comparison of the Maxwell-Jüttner, power-law, and kappa distributions

Results

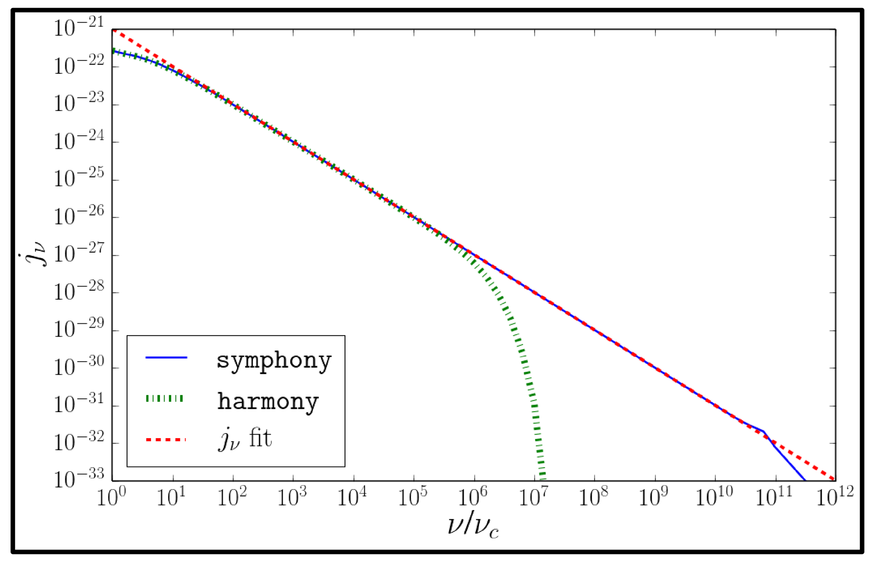
Tests of `symphony`

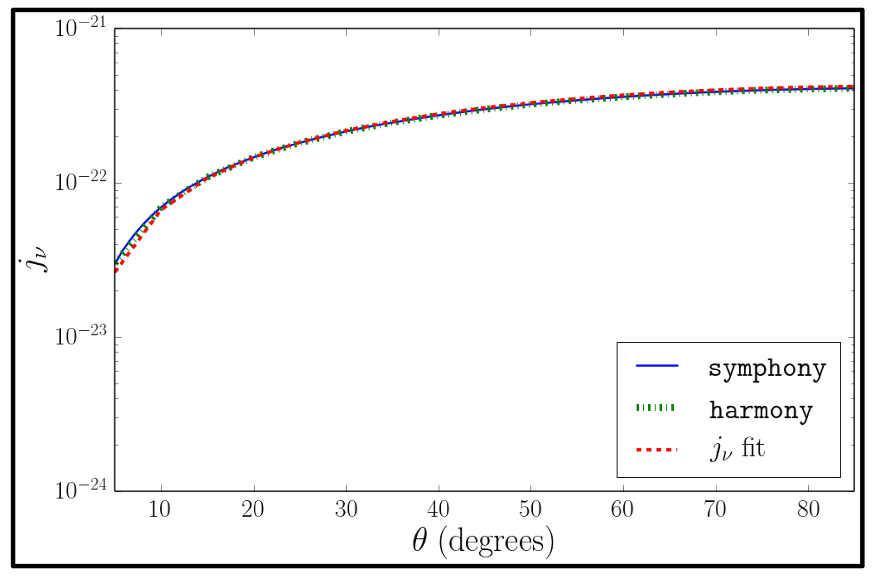
- `symphony` was tested rigorously to ensure that its results are accurate
- Tests included comparison to:
    - Known results from the literature (power-law polarization fraction)
    - Existing code (`harmony`)
    - Existing fitting formulae



The polarization fraction (ratio of polarized intensity to total intensity) is known for a power-law distribution. `symphony` gives the correct polarization fraction in the synchrotron limit.

Emission from a power-law distribution calculated by `symphony`, `harmony`, and a fitting formula. `harmony` (green) breaks down; `symphony` outperforms it by several orders of magnitude.





Emission for a relativistic thermal distribution versus observer angle θ. `symphony`, `harmony`, and an existing fitting formula agree to high precision.

Fitting formulae for all distributions and polarizations

- Using `symphony`, we were able to produce approximate fitting formulae to the emissivity and absorptivity for all three distributions and all polarizations
- These may be useful in cases where computation time is a constraint, such as large-scale supercomputer based plasma simulations

Future work

Effect of small-scale fluctuations on large-scale plasma properties

Almost all plasma simulations on the scale of the black hole accretion disk are unable to resolve fluctuations in the magnetic field, temperature, and density on the scale of the electron and ion Larmor radii (radius of the helix depicted on the leftmost panel). They instead integrate over all of these fluctuations, and use the result in their large-scale simulations.

Using `symphony` and data from a simulation that resolves Larmor scale fluctuations, we hope to determine if these small-scale fluctuations really can be integrated out without significant errors on the large scale.

Conclusions

We have produced a fast, accurate, and full-featured code, `symphony`, to calculate polarized emission and absorption coefficients for arbitrary electron energy distributions. In addition, `symphony` was used to produce fitting formulae to the studied emission and absorption coefficients. These fitting formulae may be useful to those who run large-scale plasma simulations where computation time is a constraint.

We hope to use symphony to learn more about synchrotron-emitting plasmas like those that will be imaged by the EHT.

Acknowledgments

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The majority of this work can be found in Pandya et al. 2016, Astrophysical Journal, in press.

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`symphony`

`symphony` can be found online at:

https://github.com/AFD-Illinois/symphony

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