doi:10.5281/zenodo.2578291

Making plasma research reproducible

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I. HOW REPRODUCIBLE IS PLASMA RESEARCH?

Reproducibility is a cornerstone of the scientific method. Experimental results should be able to be reproduced before those results are accepted by the broader scientific community. In 2015, the Open Science Collaborative announced astonishing results from the Reproducibility Project: Psychology.[1] Researchers worldwide attempted to reproduce results from 100 studies published in three top psychology journals in 2008. **Only 39% of the published effects were able to be replicated.** Low replication rates have also been reported for fields ranging from oncology[2] to economics.[3] The frequent inability to replicate published results has been dubbed the **reproducibility crisis** of modern science.

Physicists are reported to have high confidence that physics research is reproducible.[4] However, no large-scale studies of the reproducibility of physics or astronomy research have been performed to back up this claim. While we lack quantitative information on the reproducibility of plasma research, we are able to assess the extent to which plasma research satisfies reproducibility conditions and best practices.

Stodden et al.[5] describe necessary conditions for research to be reproducible. Research is *reviewable* if the methodology can be independently evaluated and the results can be judged for credibility, such as through peer review and journal publications. Research is *confirmable* if the results and conclusions can be obtained independently without using the equipment or software used for the original project. Research is *replicable* when tools are available for others to duplicate results, including data sets and the software used to analyze them. Research is *auditable* when the research materials are organized and archived so that the research can be evaluated later if necessary. Research that is replicable, auditable, and publicly available is deemed *open* and *reproducible*. A built-in requirement to this condition is that the data and source code be findable, accessible, interoperable, and reusable (FAIR).[6]

In order for plasma science research to be reviewable and confirmable, the experimental, computational, or theoretical methodology must be fully reported. Research publications require a detailed description of the methodology followed during a project. In principle, the description should contain all of the information necessary to recreate the results. In practice, the methodology contains most of the necessary information but may gloss over details that are not deemed important or do not fit within space constraints. This condition is not fully met for at least some fraction of plasma physics research, though the value of this fraction is hard to evaluate without performing a Reproducibility Project: Plasma Science. **Plasma science research is generally reviewable and largely confirmable.**

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All of the data and files used for the analysis must be available in order for a research project to be replicable. To place some bounds on the fraction of plasma research that is replicable, we can estimate the fraction of articles that cite either openly available source code or open access data as a proxy. Of the first fifty articles of the December 2018 issue of *Physics of Plasmas*, we found one citation of source code from the Astrophysics Source Code Library and zero citations of data sets. **Plasma research is generally not replicable, auditable, or open. Plasma research therefore usually does not meet the conditions of being reproducible.**

The cultural aspects of research and academia that contribute to the reproducibility crisis[5,7] are present in the plasma physics community too. Of particular importance is the incentive structure that is currently in place. Making research reproducible is usually not highly valued by prospective employers, funding agencies, or journals. Positive results are more valued than negative results, so negative results are much less likely to be submitted or accepted for publication. Such publication bias can increase the number of false positives beyond what is expected. Because the number of peer-reviewed publications is one of the most commonly used metrics to judge scientific output, early career scientists are likely to be at a disadvantage in the job search if they invest extra time making their data sets open access or writing documentation for their code. Improving the reproducibility of research is unlikely to help with getting tenure. The culture and incentive structure across the scientific community must change in order for reproducible research to be valued.

Threats to reproducible science that include cognitive biases, inadequate methodology, and incorrect application of statistics.[7] Practices such as hypothesizing after the results are known (HARKing)[8] and data dredging (also known as P-hacking)[9] can substantially increase the rate of false positives. These dangers can be mitigated through pre-registration of research protocols, improved statistical/methodological training, and independent statistical/methodological support.[7]

Open access to data from laboratory experiments and numerical simulations will improve reproducibility, enable data science studies, and increase the scientific return on investment. Open data policies are extremely common in astronomy and solar physics. One need only browse through an issue of *Solar Physics* or the *Astrophysical Journal* to find dozens of articles that make use of one or more open data sets. Many of these articles would not have been written if not for open access policies. A concern that has been raised in our community is that making research products openly available will lead to people using them incorrectly. Experience from the astronomy community shows this is not a significant problem. Moreover, there are times when researchers misinterpret the data they obtained,[10,11] and having new researchers investigate data sets could yield alternate interpretations. There are challenges to making data available from plasma experiments and simulations, including that data sets for plasma physics are more heterogeneous than in the astrophysical sciences. However, these challenges are surmountable.

Access to physical data needed for plasma research is often restricted. For example, access to the Atomic Data and Analysis Structure (ADAS) is largely limited to partner institutions. Even users of OPEN-ADAS are restricted from redistributing downloaded data files without prior written permission. Restrictions on data access substantially reduce the reproducibility of research that makes use of that data.

Regardless of whether or not plasma science research is included in the reproducibility crisis, implementing reproducibility best practices throughout our field will improve the quality of research and education.[12] We propose that the Plasma 2020 final report contain a chapter on enabling scientific reproducibility and investing in research infrastructure. We provide draft recommendations as a starting point for this discussion. Many of the recommendations have been adapted from previous reports and recommendations,[5–7,13–15] which we encourage the committee to review for a more in-depth perspective.

II. PROPOSED RECOMMENDATIONS

Conclusion: Reproducibility is a fundamental component of the scientific method, and yet is currently a low priority in plasma research. Plasma science would benefit from incrementally adopting reproducibility best practices over the next decade that have been effective in other scientific fields.

Recommendation: Educational institutions should teach best practices for scientific reproducibility, code development, and statistics when educating the next generation of plasma scientists.

These best practices may be worked into plasma physics coursework by either creating a new course or by incorporating these practices into existing courses. New educational materials should ideally be made openly available online so that they can be used in courses at other institutions to avoid duplication of effort. Funding agencies should support workshops or summer schools that help students and interested researchers learn the skills necessary to make research reproducible.

Recommendation: Funding agencies should invest in research intending to reproduce important previously published results, while using strategies that have been successful in other fields.

Merit review criteria often ask reviewers to evaluate the extent to which proposed activities are new, original, and innovative. This framing puts proposals to reproduce previously published results at a disadvantage, so researchers are less likely to propose replication attempts.[7] These criteria should be revised to encourage replication attempts and

The success rate of proposals to replicate prior works should be no less than the success rate of comparable proposals so that researchers are not discouraged from submitting these kinds of proposals. At least 2% of research funding should be directed to replication attempts. Funding agencies should encourage proposals that include a primary component for original research and a secondary component for attempting to reproduce previously published results. Including a component to reproduce prior important works should be considered a major strength in proposals with discovery science as the primary focus.

Recommendation: Research journals should adopt editorial policies and practices that encourage scientific reproducibility.

Journals should forge partnerships with online repositories such as Zenodo so that data and software used for publications can be made openly available, assigned a persistent identifier, and cited. Author instructions should recommend citing software and data sets, as is

done by the American Astronomical Society journals. To encourage authors to improve reproducibility of their works, journals may assign badges to articles that make data/materials available or preregister their methodology. This low-cost strategy increased the fraction of *Psychological Research* articles that made data/materials openly available by an order of magnitude.[14] Journals should have policies that explicitly allow and encourage publication of negative results and attempts to reproduce research. The review criteria should include asking referees to evaluate the reproducibility of the research described in a manuscript.

Recommendation: Employers should favorably view adoption of reproducibility best practices in hiring and tenure decisions. Creation of citable research products such as open data sets and scientific software should be considered an important part of a candidate's publication record. Performance of replication studies and reporting of negative results should be considered strengths.

The current incentive system rewards new findings more than replication studies and positive results more than negative results. Incentives should exist for performing rigourous, transparent, and reproducible research as well as for innovation and important discoveries. What is good for individual scientists should align with what is good for science.[7]

Recommendation: Science-quality data from laboratory plasma experiments should be made openly available in accordance with the FAIR guiding principles[6] within one year after the experiment was completed.

Open access to experimental data is necessary for scientific reproducibility. Data sets from publicly funded experiments should be made openly available with sufficient documentation and metadata for other researchers to analyze the results. An embargo period of up to one year before data release would provide an opportunity for the people who performed or proposed the experiments to publish results first. Funding agencies should invest in an online portal to provide access to data from multiple plasma experiments. The interface to this portal must be compliant with the Americans with Disabilities Act.[16] Any mandates or requirements to make data openly available must be fully funded.

Recommendation: DOE and/or NSF should create a proposal opportunity that would fund efforts to make previously acquired plasma data sets openly available in a modern archival format.[17]

Old data sets can potentially be used for new initiatives, including data mining, replication & re-interpretation of published results, calibration of new diagnostics, and even new exploratory science. Data can be lost when researchers move, storage media degrades due to cosmic ray bit flips, or the necessary equipment and software become unavailable. Grants to preserve these data sets can enable new science and new replication attempts later.

III. FINAL THOUGHTS

Reproducibility is a critical yet severely undervalued component of the scientific method. Incorporating reproducibility best practices into our discipline will require policy, educational, and cultural changes to our established practices. Including recommendations on enabling scientific reproducibility and investing in research infrastructure in the final report of the decadal review will provide a much needed push to our profession to make these changes to improve both plasma physics research and education.

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[12]Reproducibility best practices do not just help other researchers evaluate published research. These best practices are very much in our own self-interest. Suppose we find a sign error in the first equation in the analysis code for a paper that we are writing, which means that we have to redo all of our plots. If we followed reproducibility best practices, then we would be able to fix the sign error, commit the change in version control with a descriptive message, and remake all of our plots with a single command.

[13]National Academies of Sciences, Engineering, and Medicine, *Open Source Software Policy Options for NASA Earth and Space Sciences* (National Academies Press, 2018).

[14]M. C. Kidwell et al., "Badges to Acknowledge Open Practices: A Simple, Low-Cost, Effective Method for Increasing Transparency," PLoS Biology **14**, e1002456 (2016), 10.1371/journal.pbio.100245.

[15]National Academies of Sciences, Engineering, and Medicine, *Open Science by Design: Realizing a Vision for 21st Century Research* (National Academies Press, 2018).

[16]The screen reader inaccessibility of databases and research publications in astronomy has caused multiple blind or visually impaired students and scientists to leave the field or cut their education short within the last few years. Should a statement like this be included in the final report, developers will be reminded of this legal requirement, and the field of plasma physics will become more inclusive and accessible.

[17]This recommendation is inspired by NASA's Heliophysics Data Environment Enhancements opportunity through 2018. This opportunity may change in 2019.