Draft version July 10, 2019
Typeset using LaTeX default style in AASTeX62

EinsteinPy: Python for General Relativity*

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(Received January 1, 2018; Revised January 7, 2018; Accepted July 10, 2019)

Submitted to ApJ

ABSTRACT

This paper presents EinsteinPy (version 0.2), a community-developed Python package for gravitational and relativistic astrophysics. Python is a free, easy to use high level programming language which have seen a huge expansion in the number of its users and developers in recent years. Many great frameworks came as Python packages which provides a very high level of abstraction glancing over the dirty nitty gitties of the algorithms and provide an easy to use coding interface. One example is Keras - Framework for deep learning which has made field like deep learning to become a easy to code task for its users. This example really demonstrates the power of abstraction which is achievable in Python. The aim of the EinsteinPy is no different and is developed keeping in mind the state of a theoretical gravitational physicist with a little or no background in computer programming and trying to enter the field of numerical relativity or trying to use simulations in his research. Currently EinsteinPy supports simulation of time-like and null geodesics and calculate trajectories in different background geometries some of which are Schwarzschild, Kerr and KerrNewmann along with coordinate inter-conversion pipeline. It has a partially developed pipeline for plotting and visualization with dependencies on libraries like plotly, matplotlib etc. One of the unique feature of EinsteinPy is a sufficiently developed symbolic tensor manipulation utilites which is a great tool in itself for teaching yourself tensor algebra which for many beginner students can be overwhelmingly tricky. Currently EinsteinPy also provide few utility functions for hypersurface embedding of Schwarzschild spacetime which further will be extended to model gravitational lensing simulation. The current version of the library is in a state that can be used by any serious student of general relativity trying to get essence of this beautiful subject but is somewhere lost in the heavy mathematical formalism of the subject. EinsteinPy provides such students to really see through the equations and visualize whats really happening.

Keywords: gravitational physics, astrophysics — simulations — black holes — gravitational waves

1. INTRODUCTION

It was the time of 1915 when Einstein published his paper on general theory of relativity which proposed a elegant and rigorous framework for a relativistic theory of gravity and was generalized version of gravity free theory - special relativity which he published earlier in 1905 and since then the whole physics community was against the bold ideas of the young genius and resisted in the beginning because all people were worried that if these hypothesis true would then completely change our notion of how we percieve space and time. But sooner they started to realize the true depth in the formalism of general relativity and its ability to explain the fundamental laws of nature. After so many years its well established now that general theory of relativity is the "theory of gravity" in classical regime and all the attempts to formulate quantum theory of gravity one way or the other borrow ideas from GR. The central problem then and now remains to be the solutions of the Einstein's field equation. Many times we can study the behaviour of solutions under high degree of symmetry considerations and could even solve analytically for highly unrealistic systems but solving it

* Released on January, 8th, 2018

for problems relevant to astrophysical and gravitational physics research it still remains a big question on how to get around the problem of solving these field equations. This question is so profound that it has a separate research field which goes with the name of numerical relativity which attempts to use computer programmes to numerically obtain solutions of the equations (which would be the background geometry) for some turbulent region where most of the interesting dynamics is happening (as we can not solve for a infinitely large grid due to restrictions imposed on us by space and time complexity and computability).
The interest of the community grew when the field found applications in areas of radio astronomy, cosmology, signal processing, data mining. After so many years the field of numerical relativity has grown up to be a mature research area with vast literature on algorithms, numerical methods and theoretical formulations (from basic 3+1 decomposition formulation to more sophisticated ones). Currently there exist some very robust and involved frameworks that provide a complete programming ecosystem and have proved to an be essential tools for any numerical relativity researcher. Now on the other end of the research community are the theoretical physicists many of which have little or no programming experience and is really challenged by the fact that the usage of these frameworks demand heavy use of high level programming languages like C and C++. As described above Python provides a vast room for abstractions and no library existed at that time that do numerical relativity in Python and hence the team was hooked by this very fact of need for a python library on general relativity. Since then EinsteinPy has seen a lot of contributions from people all over the world and many "good to go" functionalities are already provided in this and previous versions. Like any other numerical relativity library EinsteinPy is made to provide a set of tools which can make numerical computations for solving Einstein's field equations an easy job for anyone who does not want to dive deep into the nitty gitties of the subject along with few very basic but powerful functionalities that could be used by anyone who wants to learn the subject of general relativity in general[1]. In further coming section we discuss with some of the features of the current as well previous version and the future plans which are yet to be implemented in the upcoming versions. Also we describe few code snippets to explain the usage of the library on which more details can be found on the organisation website[2]

2. DATA TYPES

The heart of abstraction that EinsteinPy aims to provide is achieved by some set of data structures that are specifically designed to ease with varieties of gravitational physics problems. The most important and central quantity in all of the general relativity is the metric tensor which defines the background geometry of spacetime on which all the dynamics happen. EinsteinPy provides class metric

2.1. *metric*

2.2. *plotting*

2.3. *symbolic*

2.4. *coordinates*

2.5. *hypersurface*

The default style in AASTEX v6.2 is a tight single column style, e.g. 10 point font, single spaced. The single column style is very useful for article with wide equations. It is also the easiest to style to work with since figures and tables, see Section 3, will span the entire page, reducing the need for address float sizing.

To invoke a two column style similar to the what is produced in the published PDF copy use

```
\documentclass[twocolumn]{aastex62}.
```

Note that in the two column style figures and tables will only span one column unless specifically ordered across both with the "*" flag, e.g.

```
\begin{figure*} ... \end{figure*},
\begin{table*} ... \end{table*}, and
```

[1] More details on this are given in further coming sections
[2] https://einsteinpy.org/

`\begin{deluxetable*} ... \end{deluxetable*}`.

This option is ignored in the onecolumn style.

Some other style options are outlined in the commented sections of this article. Any combination of style options can be used.

Two style options that are needed to fully use the new revision tracking feature, see Section 5, are `linenumbers` which uses the lineno style file to number each article line in the left margin and `trackchanges` which controls the revision and commenting highlight output.

There is also a new `modern` option that uses a Daniel Foreman-Mackey and David Hogg design to produce stylish, single column output that has wider left and right margins. It is designed to have fewer words per line to improve reader retention. It also looks better on devices with smaller displays such as smart phones.

For a Research Note use the `RNAAS` option which will produce a manuscript with no abstract and in the `modern` style.

3. FLOATS

Floats are non-text items that generally can not be split over a page. They also have captions and can be numbered for reference. Primarily these are figures and tables but authors can define their own. LaTeX tries to place a float where indicated in the manuscript but will move it later if there is not enough room at that location, hence the term "float".

Authors are encouraged to embed their tables and figures within the text as they are mentioned. Please do not place the figures and text at the end of the article as was the old practice. Editors and the vast majority of referees find it much easier to read a manuscript with embedded figures and tables.

Depending on the number of floats and the particular amount of text and equations present in a manuscript the ultimate location of any specific float can be hard to predict prior to compilation. It is recommended that authors textbfnot spend significant time trying to get float placement perfect for peer review. The AAS Journal's publisher has sophisticated typesetting software that will produce the optimal layout during production.

Note that authors of Research Notes are only allowed one float, either one table or one figure.

Table 1. ApJ costs from 1991 to 2013[a]

Year (1)	Subscription cost ($) (2)	Publication charges[b] ($/page) (3)
1991	600	100
1992	650	105
1993	550	103
1994	450	110
1995	410	112
1996	400	114
1997	525	115
1998	590	116
1999	575	115
2000	450	103
2001	490	90
2002	500	88
2003	450	90

Table 1 continued on next page

Table 1 *(continued)*

Year	Subscription cost ($)	Publication charges[b] ($/page)
(1)	(2)	(3)
2004	460	88
2005	440	79
2006	350	77
2007	325	70
2008	320	65
2009	190	68
2010	280	70
2011	275	68
2012	150	56
2013	140	55

[a] Adjusted for inflation

[b] Accounts for the change from page charges to digital quanta in April, 2011

Note—Note that `\colnumbers` does not work with the vertical line alignment token. If you want vertical lines in the headers you can not use this command at this time.

For authors that do want to take the time to optimize the locations of their floats there are some techniques that can be used. The simplest solution is to placing a float earlier in the text to get the position right but this option will break down if the manuscript is altered, see Table 1. A better method is to force LaTeX to place a float in a general area with the use of the optional `[placement specifier]` parameter for figures and tables. This parameter goes after `\begin{figure}`, `\begin{table}`, and `\begin{deluxetable}`. The main arguments the specifier takes are "h", "t", "b", and "!". These tell LaTeX to place the float here (or as close as possible to this location as possible), at the top of the page, and at the bottom of the page. The last argument, "!", tells LaTeX to override its internal method of calculating the float position. A sequence of rules can be created by using multiple arguments. For example, `\begin{figure}[htb!]` tells LaTeX to try the current location first, then the top of the page and finally the bottom of the page without regard to what it thinks the proper position should be. Many of the tables and figures in this article use a placement specifier to set their positions.

Note that the LaTeX `tabular` environment is not a float. Only when a `tabular` is surrounded by `\begin{table}` ... `\end{table}` is it a true float and the rules and suggestions above apply.

In AASTeX v6.2 all deluxetables are float tables and thus if they are longer than a page will spill off the bottom. Long deluxetables should begin with the `\startlongtable` command. This initiates a longtable environment. Authors might have to use `\clearpage` to isolate a long table or optimally place it within the surrounding text.

3.1. *Tables*

Tables can be constructed with LaTeX's standard table environment or the AASTeX's deluxetable environment. The deluxetable construct handles long tables better but has a larger overhead due to the greater amount of defined mark up used set up and manipulate the table structure. The choice of which to use is up to the author. Examples of both environments are used in this manuscript. Table 1 is a simple deluxetable example that gives the approximate changes in the subscription costs and author publication charges from 1991 to 2013.

Tables longer than 200 data lines and complex tables should only have a short example table with the full data set available in the machine readable format. The machine readable table will be available in the HTML version of the article with just a short example in the PDF. Authors are required to indicate to the reader where the data can be obtained in the table comments. Suggested text is given in the comments of Table 2. Authors are encouraged to create their own machine readable tables using the online tool at http://authortools.aas.org/MRT/upload.html.

AASTeX v6 introduces five new table features that are designed to make table construction easier and the resulting display better for AAS Journal authors. The items are:

1. Declaring math mode in specific columns,
2. Column decimal alignment,
3. Automatic column header numbering,
4. Hiding columns, and
5. Splitting wide tables into two or three parts.

Each of these new features are illustrated in following Table examples. All five features work with the regular LaTeX tabular environment and in AASTeX's deluxetable environment. The examples in this manuscript also show where the two process differ.

3.1.1. *Column math mode*

Both the LaTeX tabular and AASTeX deluxetable require an argument to define the alignment and number of columns. The most common values are "c", "l" and "r" for center, left, and right justification. If these values are capitalized, e.g. "C", "L", or "R", then that specific column will automatically be in math mode meaning that $s are not required. Note that having embedded dollar signs in the table does not affect the output. The third and forth columns of Table 2 shows how this math mode works.

3.1.2. *Decimal alignment*

Aligning a column by the decimal point can be difficult with only center, left, and right justification options. It is possible to use phantom calls in the data, e.g. `\phn`, to align columns by hand but this can be tedious in long or complex tables. To address this AASTeX introduces the `\decimals` command and a new column justification option, "D", to align data in that column on the decimal. In deluxetable the `\decimals` command is invoked before the `\startdata` call but can be anywhere in LaTeX's tabular environment.

Two other important thing to note when using decimal alignment is that each decimal column *must end with a space before the ampersand*, e.g. "&&" is not allowed. Empty decimal columns are indicated with a decimal, e.g. ".". Do not use deluxetable's `\nodata` command.

Table 2. Column math mode in an observation log

UT start time[a] (YYYY-mm-dd)	MJD start time[a] (d)	Seeing (arcsec)	Filter	Inst.
2012-03-26	56012.997	$\sim 0.''5$	Hα	NOT
2012-03-27	56013.944	$1.''5$	grism	SMARTS
2012-03-28	56014.984	$\cdots$	F814M	HST
2012-03-30	56016.978	$1.''5 \pm 0.25$	B&C	Bok

[a] At exposure start.

Note—The "C" command column identifier in the 3 column turns on math mode for that specific column. One could do the same for the next column so that dollar signs would not be needed for Hα but then all the other text would also be in math mode and thus typeset in Latin Modern math and you will need to put it back to Roman by hand. Note that if you do change this column to math mode the dollar signs already present will not cause a problem. Table 2 is published in its entirety in the machine readable format. A portion is shown here for guidance regarding its form and content.

The “D” alignment token works by splitting the column into two parts on the decimal. While this is invisible to the user one must be aware of how it works so that the headers are accounted for correctly. All decimal column headers need to span two columns to get the alignment correct. This can be done with a multicolumn call, e.g `\multicolumn2c{}` or `\multicolumn{2}{c}{}`, or use the new `\twocolhead{}` command in deluxetable. Since LaTeX is splitting these columns into two it is important to get the table width right so that they appear joined on the page. You may have to run the LaTeX compiler twice to get it right. Table 3 illustrates how decimal alignment works in the tabular environment with a ± symbol embedded between the last two columns.

Table 3. Decimal alignment made easy

Column	Value		Uncertainty
A	1234	±	100.0
B	123.4	±	10.1
C	12.34	±	1.01
D	1.234	±	0.101
E	.1234	±	0.01001
F	1.0	±	

NOTE. - Two decimal aligned columns

3.1.3. *Automatic column header numbering*

The command `\colnumbers` can be included to automatically number each column as the last row in the header. Per the AAS Journal table format standards, each column index numbers will be surrounded by parentheses. In a LaTeX tabular environment the `\colnumbers` should be invoked at the location where the author wants the numbers to appear, e.g. after the last line of specified table header rows. In deluxetable this command has to come before `\startdata`. `\colnumbers` will not increment for columns hidden by the “h” command, see Section 3.1.4. Table 1 uses this command to automatically generate column index numbers.

Note that when using decimal alignment in a table the command `\decimalcolnumbers` must be used instead of `\colnumbers` and `\decimals`. Table 4 illustrates this specific functionality.

3.1.4. *Hiding columns*

Entire columns can be hidden from display simply by changing the specified column identifier to “h”. In the LaTeX tabular environment this column identifier conceals the entire column including the header columns. In AASTeX’s deluxetables the header row is specifically declared with the `\tablehead` call and each header column is marked with `\colhead` call. In order to make a specific header disappear with the “h” column identifier in deluxetable use `\nocolhead` instead to suppress that particular column header.

Authors can use this option in many different ways. Since column data can be easily suppressed authors can include extra information and hid it based on the comments of co-authors or referees. For wide tables that will have a machine readable version, authors could put all the information in the LaTeX table but use this option to hid as many columns as needed until it fits on a page. This concealed column table would serve as the example table for the full machine readable version. Regardless of how columns are obscured, authors are responsible for removing any unneeded column data or alerting the editorial office about how to treat these columns during production for the final typeset article.

Table 4 provides some basic information about the first ten Messier Objects and illustrates how many of these new features can be used together. It has automatic column numbering, decimal alignment of the distances, and one concealed column. The Common name column is the third in the LaTeX deluxetable but does not appear when the article is compiled. This hidden column can be shown simply by changing the “h” in the column identifier preamble to another valid value. This table also uses `\tablenum` to renumber the table because a LaTeX tabular table was inserted before it.

3.1.5. *Splitting a table into multiple horizontal components*

Since the AAS Journals are now all electronic with no print version there is no reason why tables can not be as wide as authors need them to be. However, there are some artificial limitations based on the width of a print page. The

Table 4. Fun facts about the first 10 messier objects

Messier Number (1)	NGC/IC Number (2)	Object Type (3)	Distance (kpc) (4)	Constellation (5)	V (mag) (6)
M1	NGC 1952	Supernova remnant	2	Taurus	8.4
M2	NGC 7089	Cluster, globular	11.5	Aquarius	6.3
M3	NGC 5272	Cluster, globular	10.4	Canes Venatici	6.2
M4	NGC 6121	Cluster, globular	2.2	Scorpius	5.9
M5	NGC 5904	Cluster, globular	24.5	Serpens	5.9
M6	NGC 6405	Cluster, open	0.31	Scorpius	4.2
M7	NGC 6475	Cluster, open	0.3	Scorpius	3.3
M8	NGC 6523	Nebula with cluster	1.25	Sagittarius	6.0
M9	NGC 6333	Cluster, globular	7.91	Ophiuchus	8.4
M10	NGC 6254	Cluster, globular	4.42	Ophiuchus	6.4

Note—This table "hides" the third column in the LaTeX when compiled. The Distance is also centered on the decimals. Note that when using decimal alignment you need to include the `\decimals` command before `\startdata` and all of the values in that column have to have a space before the next ampersand.

Figure 1. Swift/XRT X-ray light curves of RS Oph and U Sco which represent the two canonical recurrent types, a long period system with a red giant secondary and a short period system with a dwarf/sub-dwarf secondary, respectively.

old way around this limitation was to rotate into landscape mode and use the smallest available table font sizes, e.g. `\tablewidth`, to get the table to fit. Unfortunately, this was not alway enough but now along with the hide column option outlined in Section 3.1.4 there is a new way to break a table into two or three components so that it flows down a page by invoking a new table type, splittabular or splitdeluxetable. Within these tables a new "B" column separator is introduced. Much like the vertical bar option, "|", that produces a vertical table lines, e.g. Table 1, the new "B" separator indicates where to Break a table. Up to two "B"s may be included.

Table 5 shows how to split a wide deluxetable into three parts with the `\splitdeluxetable` command. The `\colnumbers` option is on to show how the automatic column numbering carries through the second table component, see Section 3.1.3.

The last example, Table 6, shows how to split the same table but with a regular LaTeX tabular call and into two parts. Decimal alignment is included in the third column and the "Component" column is hidden to illustrate the new features working together.

3.2. *Figures*

Authors can include a wide number of different graphics with their articles in encapsulated postscript (EPS) or portable document format (PDF). These range from general figures all authors are familiar with to new enhanced graphics that can only be fully experienced in HTML. The later include animations, figure sets and interactive figures. This portion of the article provides examples for setting up all these graphics in with the latest version of AASTeX.

3.3. *General figures*

AASTeX has a `\plotone` command to display a figure consisting of one EPS/PDF file. Figure **??** is an example which uses the data from Table 1. For a general figure consisting of two EPS/PDF files the `\plottwo` command can be used to position the two image files side by side. Figure 1 shows the Swift/XRT X-ray light curves of two recurrent novae. The data from Figures 1 through 2 are taken from Table 2 of Schwarz et al. (2011).

Table 5. Measurements of Emission Lines: two breaks

Model	Component	Shift (km s^{-1})	FWHM (km s^{-1})	Flux (10^{-17} erg s^{-1} cm^{-2}) Lyα
(1)	(2)	(3)	(4)	(5)
	BELs	-97.13	9117±38	1033±33
Model 1	IELs	-4049.123	1974±22	2495±30
	NELs	···	641±4	449±23
	BELs	-85	8991±41	988±29
Model 2	IELs	-51000	2025±26	2494±32
	NELs	52	637±10	477±17

N V	Si IV	C IV	Mg II	Hγ
(6)	(7)	(8)	(9)	(10)
< 35	< 166	637±31	1951±26	991±30
< 42	< 109	995±186	83±30	75±23
< 6	< 9	–	275±18	150±11
< 24	< 173	623±28	1945±29	989±27
< 37	< 124	1005±190	72±28	72±21
< 4	< 8	–	278±17	153±10

Hβ	Hα	He I	Paγ
(11)	(12)	(13)	(14)
3502±42	20285±80	2025±116	1289±107
130±25	357±94	194±64	36±23
313±12	958±43	318±34	151±17
3498±37	20288±73	2047±143	1376±167
113±18	271±85	205±72	34±21
317±15	969±40	325±37	147±22

Note—This is an example of how to split a deluxetable. You can split any table with this command into two or three parts. The location of the split is given by the author based on the placement of the "B" indicators in the column identifier preamble. For more information please look at the new AASTEX instructions.

Both `\plotone` and `\plottwo` take a `\caption` and an optional `\figurenum` command to specify the figure number[3]. Each is based on the `graphicx` package command, `\includegraphics`. Authors are welcome to use `\includegraphics` along with its optional arguments that control the height, width, scale, and position angle of a file within the figure. More information on the full usage of `\includegraphics` can be found at https://en.wikibooks.org/wiki/LaTeX/Importing_Graphics#Including_graphics.

3.4. *Grid figures*

Including more than two EPS/PDF files in a single figure call can be tricky easily format. To make the process easier for authors AASTEX v6 offers `\gridline` which allows any number of individual EPS/PDF file calls within a single figure. Each file cited in a `\gridline` will be displayed in a row. By adding more `\gridline` calls an author can easily construct a matrix X by Y individual files as a single general figure.

For each `\gridline` command a EPS/PDF file is called by one of four different commands. These are `\fig`, `\rightfig`, `\leftfig`, and `\boxedfig`. The first file call specifies no image position justification while the next two

[3] It is better to not use `\figurenum` and let LaTeX auto-increment all the figures. If you do use this command you need to mark all of them accordingly.

Table 6. Measurements of Emission Lines: one break

Model	Shift ($\mathrm{km\ s^{-1}}$)	FWHM ($\mathrm{km\ s^{-1}}$)	Flux (10^{-17} erg $\mathrm{s^{-1}}$ $\mathrm{cm^{-2}}$)									
			Lyα	N V	Si IV	C IV	Mg II	Hγ	Hβ	Hα	He I	Paγ
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	-97.13	9117±38	1033±33	< 35	< 166	637±31	1951±26	991±30	3502±42	20285±80	2025±116	1289±107
Model 1	-4049.123	1974±22	2495±30	< 42	< 109	995±186	83±30	75±23	130±25	357±94	194±64	36±23
		641±4	449±23	< 6	< 9	–	275±18	150±11	313±12	958±43	318±34	151±17
	-85	8991±41	988±29	< 24	< 173	623±28	1945±29	989±27	3498±37	20288±73	2047±143	1376±167
Model 2	-51000	2025±26	2494±32	< 37	< 124	1005±190	72±28	72±21	113±18	271±85	205±72	34±21
	52	637±10	477±17	< 4	< 8	–	278±17	153±10	317±15	969±40	325±37	147±22

Figure 2. The Swift/XRT X-ray light curve for the first year after outburst of the suspected recurrent nova KT Eri. At a maximum count rate of 328 ct/s, KT Eri was the brightest nova in X-rays observed to date. All the component figures are available in the Figure Set.

will right and left justify the image, respectively. The `\boxedfig` is similar to `\fig` except that a box is drawn around the figure file when displayed. Each of these commands takes three arguments. The first is the file name. The second is the width that file should be displayed at. While any natural LaTEX unit is allowed, it is recommended that author use fractional units with the `\textwidth`. The last argument is text for a subcaption.

Figure **??** shows an inverted pyramid of individual figure constructed with six individual EPS files using the `\gridline` option.

3.5. *Figure sets*

A large collection of similar style figures should be grouped together as a figure set. The derived PDF article will only shows an example figure while the enhanced content is available in the figure set in the electronic edition. The advantage of a figure set gives the reader the ability to easily sort through the figure collection to find individual component figures. All of the figure set components, along with their html framework, are also available for download in a .tar.gz package.

Special LaTEX mark up is required to create a figure set. Prior to AASTEX v6 the underlying mark up commands had to be inserted by hand but is now included. Note that when an article with figure set is compiled in LaTEX none of the component figures are shown and a floating Figure Set caption will appear in the resulting PDF.

Fig. Set 4. Swift X-ray light curves

Authors are encouraged to use an online tool at http://authortools.aas.org/FIGSETS/make-figset.html to generate their own specific figure set mark up to incorporate into their LaTEX articles.

3.6. *Animations*

Authors may include animations in their articles. A single still frame from the animation should be included as a regular figure to serve as an example. The associated figure caption should indicate to the reader exactly what the animation shows and that the animation is available online.

Figure 3. Example image from the animation which is available in the electronic edition.

3.7. *Interactive figures*

Interactive figures give the reader the ability to manipulate the information contained in an image which can add clarity or help further the author's narrative. These figures consist of two parts, the figure file in a specific format and a javascript and html frame work that provides the interactive control. An example of an interactive figure is a 3D model. The underlying figure is a X3D file while x3dom.js is the javascript driver that displays it. An author created interface is added via a html wrapper. The first 3D model published by the AAS Journals using this technique was Vogt et al. (2014). Authors should consult the online tutorials for more information on how to construct their own interactive figures.

As with animations authors should include a non-interactive regular figure to use as an example. The example figure should also indicate to the reader that the enhanced figure is interactive and can be accessed online.

4. DISPLAYING MATHEMATICS

The most common mathematical symbols and formulas are in the amsmath package. AASTEX requires this package so there is no need to specifically call for it in the document preamble. Most modern LaTEX distributions already contain this package. If you do not have this package or the other required packages, revtex4-1, latexsym, graphicx, amssymb, longtable, and epsf, they can be obtained from http://www.ctan.org

Mathematics can be displayed either within the text, e.g. $E = mc^2$, or separate from in an equation. In order to be properly rendered, all inline math text has to be declared by surrounding the math by dollar signs ($).

A complex equation example with inline math as part of the explanation follows.

$$\bar{v}(p_2,\sigma_2)P_{-\tau}\hat{a}_1\hat{a}_2\cdots\hat{a}_n u(p_1,\sigma_1), \tag{1}$$

where p and σ label the initial $e^{\pm}$ four-momenta and helicities ($\sigma = \pm 1$), $\hat{a}_i = a_i^{\mu}\gamma_{\nu}$ and $P_{\tau} = \frac{1}{2}(1+\tau\gamma_5)$ is a chirality projection operator ($\tau = \pm 1$). This produces a single line formula. LaTEX will auto-number this and any subsequent equations. If no number is desired then the `equation` call should be replaced with `displaymath`.

LaTEX can also handle a a multi-line equation. Use `eqnarray` for more than one line and end each line with a \\. Each line will be numbered unless the \\ is preceded by a `\nonumber` command. Alignment points can be added with ampersands (&). There should be two ampersands per line. In the examples they are centered on the equal symbol.

$$\gamma^{\mu} = \begin{pmatrix} 0 & \sigma_{+}^{\mu} \\ \sigma_{-}^{\mu} & 0 \end{pmatrix}, \gamma^5 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}, \tag{2}$$

$$\sigma_{\pm}^{\mu} = (\mathbf{1}, \pm\sigma), \tag{3}$$

$$\begin{aligned} \hat{a} &= \begin{pmatrix} 0 & (\hat{a})_{+} \\ (\hat{a})_{-} & 0 \end{pmatrix}, \\ (\hat{a})_{\pm} &= a_{\mu}\sigma_{\pm}^{\mu} \end{aligned} \tag{4}$$

5. REVISION TRACKING AND COLOR HIGHLIGHTING

Authors sometimes use color to highlight changes to their manuscript in response to editor and referee comments. In AASTEX new commands have been introduced to make this easier and formalize the process.

The first method is through a new set of editing mark up commands that specifically identify what has been changed. These commands are \added{<text>}, \deleted{<text>}, and \replaced{<old text>}{<replaced text>}. To activate these commands the trackchanges option must be used in the \documentclass call. When compiled this will produce the marked text in red. The \explain{<text>} can be used to add text to provide information to the reader describing the change. Its output is purple italic font. To see how \added{<important added info>}, \deleted{<this can be deleted text>}, \replaced{<old data>}{<replaced data>}, and \explain{<text explaining the change>} commands will produce important added information and replaced data, toggle between versions compiled with and without the trackchanges option.

A summary list of all these tracking commands can be produced at the end of the article by adding the \listofchanges just before the \end{document} call. The page number for each change will be provided. If the linenumbers option is also included in the documentcall call then not only will all the lines in the article be numbered for handy reference but the summary list will also include the line number for each change.

The second method does not have the ability to highlight the specific nature of the changes but does allow the author to document changes over multiple revisions. The commands are \edit1{<text>}, \edit2{<text>} and \edit3{<text>} and they produce <text> that is highlighted in bold red, italic blue and underlined purple, respectively. Authors should use the first command to **indicated which text has been changed from the first revision.** The second command is to highlight *new or modified text from a second revision*. If a third revision is needed then the last command should be used to show this changed text. Since over 90% of all manuscripts are accepted after the 3rd revision these commands make it easy to identify what text has been added and when. Once the article is accepted all the highlight color can be turned off simply by adding the \turnoffediting command in the preamble. Likewise, the new commands \turnoffeditone, \turnoffedittwo, and \turnoffeditthree can be used to only turn off the \edit1{<text>}, \edit2{<text>} and \edit3{<text>}, respectively.

Similar to marking editing changes with the \edit options there are also the \authorcomments1{<text>}, \authorcomments2{<text>} and \authorcomments3{<text>} commands. These produce the same bold red, italic blue and underlined purple text but when the \turnoffediting command is present the <text> material does not appear in the manuscript. Authors can use these commands to mark up text that they are not sure should appear in the final manuscript or as a way to communicate comments between co-authors when writing the article.

6. SOFTWARE AND THIRD PARTY DATA REPOSITORY CITATIONS

The AAS Journals would like to encourage authors to change software and third party data repository references from the current standard of a footnote to a first class citation in the bibliography. As a bibliographic citation these important references will be more easily captured and credit will be given to the appropriate people.

The first step to making this happen is to have the data or software in a long term repository that has made these items available via a persistent identifier like a Digital Object Identifier (DOI). A list of repositories that satisfy this criteria plus each one's pros and cons are given at https://github.com/AASJournals/Tutorials/tree/master/Repositories.

In the bibliography the format for data or code follows this format:

author year, title, version, publisher, prefix:identifier

Corrales (2015) provides a example of how the citation in the article references the external code at https://doi.org/10.5281/zenod Unfortunately, bibtex does not have specific bibtex entries for these types of references so the "@misc" type should be used. The Repository tutorial explains how to code the "@misc" type correctly. The most recent aasjournal.bst file, available with AASTEX v6, will output bibtex "@misc" type properly.

We thank all the people that have made this AASTeX what it is today. This includes but not limited to Bob Hanisch, Chris Biemesderfer, Lee Brotzman, Pierre Landau, Arthur Ogawa, Maxim Markevitch, Alexey Vikhlinin and Amy Hendrickson. Also special thanks to David Hogg and Daniel Foreman-Mackey for the new "modern" style design. Considerable help was provided via bug reports and hacks from numerous people including Patricio Cubillos, Alex Drlica-Wagner, Sean Lake, Michele Bannister, Peter Williams, and Jonathan Gagne.

Facilities: HST(STIS), Swift(XRT and UVOT), AAVSO, CTIO:1.3m, CTIO:1.5m,CXO

Software: astropy (Astropy Collaboration et al. 2013), Cloudy (Ferland et al. 2013), SExtractor (Bertin & Arnouts 1996)

APPENDIX

A. APPENDIX INFORMATION

Appendices can be broken into separate sections just like in the main text. The only difference is that each appendix section is indexed by a letter (A, B, C, etc.) instead of a number. Likewise numbered equations have the section letter appended. Here is an equation as an example.

$$I = \frac{1}{1 + d_1^{P(1+d_2)}} \tag{A1}$$

Appendix tables and figures should not be numbered like equations. Instead they should continue the sequence from the main article body.

B. AUTHOR PUBLICATION CHARGES

Finally some information about the AAS Journal's publication charges. In April 2011 the traditional way of calculating author charges based on the number of printed pages was changed. The reason for the change was due to a recognition of the growing number of article items that could not be represented in print. Now author charges are determined by a number of digital "quanta". A single quantum is 350 words, one figure, one table, and one enhanced digital item. For the latter this includes machine readable tables, figure sets, animations, and interactive figures. The current cost is $27 per word quantum and $30 for all other quantum type.

C. ROTATING TABLES

The process of rotating tables into landscape mode is slightly different in AASTEXv6.2. Instead of the `\rotate` command, a new environment has been created to handle this task. To place a single page table in a landscape mode start the table portion with `\begin{rotatetable}` and end with `\end{rotatetable}`.

Tables that exceed a print page take a slightly different environment since both rotation and long table printing are required. In these cases start with `\begin{longrotatetable}` and end with `\end{longrotatetable}`. Table 7 is an example of a multi-page, rotated table.

Table 7. Observable Characteristics of Galactic/Magellanic Cloud novae with X-ray observations

Name	V_{max}	Date	t_2	FWHM	E(B-V)	N_H	Period	D	Dust?	RN?
	(mag)	(JD)	(d)	(km s^{-1})	(mag)	(cm^{-2})	(d)	(kpc)		
CI Aql	8.83 (1)	2451665.5 (1)	32 (2)	2300 (3)	0.8±0.2 (4)	1.2e+22	0.62 (4)	6.25±5 (4)	N	Y
CSS081007	···	2454596.5	···	···	0.146	1.1e+21	1.77 (5)	4.45±1.95 (6)	···	···
GQ Mus	7.2 (7)	2445352.5 (7)	18 (7)	1000 (8)	0.45 (9)	3.8e+21	0.059375 (10)	4.8±1 (9)	N (7)	···
IM Nor	7.84 (11)	2452289 (2)	50 (2)	1150 (12)	0.8±0.2 (4)	8e+21	0.102 (13)	4.25±3.4 (4)	N	Y
KT Eri	5.42 (14)	2455150.17 (14)	6.6 (14)	3000 (15)	0.08 (15)	5.5e+20	···	6.5 (15)	N	M
LMC 1995	10.7 (16)	2449778.5 (16)	15±2 (17)	···	0.15 (203)	7.8e+20	···	50	···	···
LMC 2000	11.45 (18)	2451737.5 (18)	9±2 (19)	1700 (20)	0.15 (203)	7.8e+20	···	50	···	···
LMC 2005	11.5 (21)	2453700.5 (21)	63 (22)	900 (23)	0.15 (203)	1e+21	···	50	M (24)	···
LMC 2009a	10.6 (25)	2454867.5 (25)	4±1	3900 (25)	0.15 (203)	5.7e+20	1.19 (26)	50	N	Y
SMC 2005	10.4 (27)	2453588.5 (27)	···	3200 (28)	···	5e+20	···	61	···	···
QY Mus	8.1 (29)	2454739.90 (29)	60:	···	0.71 (30)	4.2e+21	···	···	M	···
RS Oph	4.5 (31)	2453779.44 (14)	7.9 (14)	3930 (31)	0.73 (32)	2.25e+21	456 (33)	1.6±0.3 (33)	N (34)	Y
U Sco	8.05 (35)	2455224.94 (35)	1.2 (36)	7600 (37)	0.2±0.1 (4)	1.2e+21	1.23056 (36)	12±2 (4)	N	Y
V1047 Cen	8.5 (38)	2453614.5 (39)	6 (40)	840 (38)	···	1.4e+22	···	···	···	···
V1065 Cen	8.2 (41)	2454123.5 (41)	11 (42)	2700 (43)	0.5±0.1 (42)	3.75e+21	···	9.05±2.8 (42)	Y (42)	···
V1187 Sco	7.4 (44)	2453220.5 (44)	7: (45)	3000 (44)	1.56 (44)	8.0e+21	···	4.9±0.5 (44)	N	···
V1188 Sco	8.7 (46)	2453577.5 (46)	7 (40)	1730 (47)	···	5.0e+21	···	7.5 (39)	···	···
V1213 Cen	8.53 (48)	2454959.5 (48)	11±2 (49)	2300 (50)	2.07 (30)	1.0e+22	···	···	···	···
V1280 Sco	3.79 (51)	2454147.65 (14)	21 (52)	640 (53)	0.36 (54)	1.6e+21	···	1.6±0.4 (54)	Y (54)	···
V1281 Sco	8.8 (55)	2454152.21 (55)	15:	1800 (56)	0.7 (57)	3.2e+21	···	···	N	···
V1309 Sco	7.1 (58)	2454714.5 (58)	23±2 (59)	670 (60)	1.2 (30)	4.0e+21	···	···	···	···
V1494 Aql	3.8 (61)	2451515.5 (61)	6.6±0.5 (61)	1200 (62)	0.6 (63)	3.6e+21	0.13467 (64)	1.6±0.1 (63)	N	···
V1663 Aql	10.5 (65)	2453531.5 (65)	17 (66)	1900 (67)	2: (68)	1.6e+22	···	8.9±3.6 (69)	N	···
V1974 Cyg	4.3 (70)	2448654.5 (70)	17 (71)	2000 (19)	0.36±0.04 (71)	2.7e+21	0.081263 (70)	1.8±0.1 (72)	N	···
V2361 Cyg	9.3 (73)	2453412.5 (73)	6 (40)	3200 (74)	1.2: (75)	7.0e+21	···	···	Y (40)	···
V2362 Cyg	7.8 (76)	2453831.5 (76)	9 (77)	1850 (78)	0.575±0.015 (79)	4.4e+21	0.06577 (80)	7.75±3 (77)	Y (81)	···
V2467 Cyg	6.7 (82)	2454176.27 (82)	7 (83)	950 (82)	1.5 (84)	1.4e+22	0.159 (85)	3.1±0.5 (86)	M (87)	···
V2468 Cyg	7.4 (88)	2454534.2 (88)	10:	1000 (88)	0.77 (89)	1.0e+22	0.242 (90)	···	N	···
V2491 Cyg	7.54 (91)	2454567.86 (91)	4.6 (92)	4860 (93)	0.43 (94)	4.7e+21	0.09580: (95)	10.5 (96)	N	M
V2487 Oph	9.5 (97)	2450979.5 (97)	6.3 (98)	10000 (98)	0.38±0.08 (98)	2.0e+21	···	27.5±3 (99)	N (100)	Y (101)
V2540 Oph	8.5 (102)	2452295.5 (102)	···	···	···	2.3e+21	0.284781 (103)	5.2±0.8 (103)	N	···
V2575 Oph	11.1 (104)	2453778.8 (104)	20:	560 (104)	1.4 (105)	3.3e+21	···	···	N (105)	···
V2576 Oph	9.2 (106)	2453832.5 (106)	8:	1470 (106)	0.25 (107)	2.6e+21	···	···	N	···
V2615 Oph	8.52 (108)	2454187.5 (108)	26.5 (108)	800 (109)	0.9 (108)	3.1e+21	···	3.7±0.2 (108)	Y (110)	···
V2670 Oph	9.9 (111)	2454613.11 (111)	15:	600 (112)	1.3: (113)	2.9e+21	···	···	N (114)	···
V2671 Oph	11.1 (115)	2454617.5 (115)	8:	1210 (116)	2.0 (117)	3.3e+21	···	···	M (117)	···

Table 7 continued on next page

Table 7 *(continued)*

Name	V_{max} (mag)	Date (JD)	t_2 (d)	FWHM (km s^{-1})	E(B-V) (mag)	N_H (cm^{-2})	Period (d)	D (kpc)	Dust?	RN?
V2672 Oph	10.0 (118)	2455060.02 (118)	2.3 (119)	8000 (118)	1.6±0.1 (119)	4.0e+21	···	19±2 (119)	···	M
V351 Pup	6.5 (120)	2448617.5 (120)	16 (121)	···	0.72±0.1 (122)	6.2e+21	0.1182 (123)	2.7±0.7 (122)	N	···
V382 Nor	8.9 (124)	2453447.5 (124)	12 (40)	1850 (23)	···	1.7e+22	···	···	···	···
V382 Vel	2.85 (125)	2451320.5 (125)	4.5 (126)	2400 (126)	0.05: (126)	3.4e+21	0.146126 (127)	1.68±0.3 (126)	N	···
V407 Cyg	6.8 (128)	2455266.314 (128)	5.9 (129)	2760 (129)	0.5±0.05 (130)	8.8e+21	15595 (131)	2.7 (131)	···	Y
V458 Vul	8.24 (132)	2454322.39 (132)	7 (133)	1750 (134)	0.6 (135)	3.6e+21	0.06812255 (136)	8.5±1.8 (133)	N (135)	···
V459 Vul	7.57 (137)	2454461.5 (137)	18 (138)	910 (139)	1.0 (140)	5.5e+21	···	3.65±1.35 (138)	Y (140)	···
V4633 Sgr	7.8 (141)	2450895.5 (141)	19±3 (142)	1700 (143)	0.21 (142)	1.4e+21	0.125576 (144)	8.9±2.5 (142)	N	···
V4643 Sgr	8.07 (145)	2451965.867 (145)	4.8 (146)	4700 (147)	1.67 (148)	1.4e+22	···	3 (148)	N	···
V4743 Sgr	5.0 (149)	2452537.5 (149)	9 (150)	2400 (149)	0.25 (151)	1.2e+21	0.281 (152)	3.9±0.3 (151)	N	···
V4745 Sgr	7.41 (153)	2452747.5 (153)	8.6 (154)	1600 (155)	0.1 (154)	9.0e+20	0.20782 (156)	14±5 (154)	···	···
V476 Sct	10.3 (157)	2453643.5 (157)	15 (158)	···	1.9 (158)	1.2e+22	···	4±1 (158)	M (159)	···
V477 Sct	9.8 (160)	2453655.5 (160)	3 (160)	2900 (161)	1.2: (162)	4e+21	···	···	M (163)	···
V5114 Sgr	8.38 (164)	2453081.5 (164)	11 (165)	2000 (23)	···	1.5e+21	···	7.7±0.7 (165)	N (166)	···
V5115 Sgr	7.7 (167)	2453459.5 (167)	7 (40)	1300 (168)	0.53 (169)	2.3e+21	···	···	N (169)	···
V5116 Sgr	8.15 (170)	2453556.91 (170)	6.5 (171)	970 (172)	0.25 (173)	1.5e+21	0.1238 (171)	11±3 (173)	N (174)	···
V5558 Sgr	6.53 (175)	2454291.5 (175)	125 (176)	1000 (177)	0.80 (178)	1.6e+22	···	1.3±0.3 (176)	N (179)	···
V5579 Sgr	5.56 (180)	2454579.62 (180)	7:	1500 (23)	1.2 (181)	3.3e+21	···	···	Y (181)	···
V5583 Sgr	7.43 (182)	2455051.07 (182)	5:	2300 (182)	0.39 (30)	2.0e+21	···	10.5	···	···
V574 Pup	6.93 (183)	2453332.22 (183)	13 (184)	2800 (184)	0.5±0.1	6.2e+21	···	6.5±1	M (185)	···
V597 Pup	7.0 (186)	2454418.75 (186)	3:	1800 (187)	0.3 (188)	5.0e+21	0.11119 (189)	···	N (188)	···
V598 Pup	3.46 (14)	2454257.79 (14)	9±1 (190)	···	0.16 (190)	1.4e+21	···	2.95±0.8 (190)	···	···
V679 Car	7.55 (191)	2454797.77 (191)	20:	···	···	1.3e+22	···	···	···	···
V723 Cas	7.1 (192)	2450069.0 (192)	263 (2)	600 (193)	0.5 (194)	2.35e+21	0.69 (195)	3.86±0.23 (196)	N	···
V838 Her	5 (197)	2448340.5 (197)	2 (198)	···	0.5±0.1 (198)	2.6e+21	0.2975 (199)	3±1 (198)	Y (200)	···
XMMSL1 J06	12 (201)	2453643.5 (202)	8±2 (202)	···	0.15 (203)	8.7e+20	···	50	···	···

A handy "cheat sheat" that provides the necessary LaTeX to produce 17 different types of tables is available at http://journals.aas.org/authors/aastex/aasguide.html#table_cheat_sheet.

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