The Past, Present and Future of Visualization in Astronomy

Alyssa A. Goodman (and MANY others!)
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Why have astronomers been obsessed with visualization forever?

Our Universe is not two-dimensional, but the Sky is.
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100 AD–16th Century

17th Century

21st Century

“The Path to Newton”

100 years of Perseus

+2 Challenges... “case” as a variable... 3D selection
Illustration of the Ptolemaic geocentric model of the Universe by Bartolomeu Velho. Taken from Cosmographia (Biblioteca National, Paris).
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100 AD—16th Century

PTOLEMY
100–170
Greek living in Roman Egypt

Epicycles, equants, eccentrics

17th Century

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The Path to Newton

**Prevailing Belief**

- **Concerned with Phenomena**
  - Gnomon
  - Arithmetic & Accounting: Zero as Place Holder
  - Planar Geometry
- **Earth at Center**
  - Believed Sun at Center
  - Arithmetic: Zero as Place Holder
  - Planar Geometry: Spherical Geometry
  - Trigonometry

**Math Available**

- Greek: Natural, not supernatural.
- Greek: Nature can be explained.
- Greek: Motion needs a little push.
- Greek: Motion must have a cause.
- Greek: Symmetry rules.
- Greek: Motion and change are illusions.
- Greek: Question all you “see.”
- Greek: Earth is stationary center of the universe.
- Greek: Earth is WAY bigger than you might think.
- Greek: Universe is spherical.
- Greek: If circles are perfect, spheres are sublime.

**Big Ideas**

- Correct
- Partial credit
- Wrong

**Connections Between Ideas**

- Teacher-Pupil or Senior-Junior Researcher
- Travel between cultures

**Published works**

- Aristote: Physics, Aristotle: Physics, c. 350 BCE
- Elements: Euclid, Elements, c. 300 BCE
- The Almagest: Ptolemy, The Almagest, c. 150
- Al-Biruni: Astronomical Diaries

**Tools Available**

- Greek: Hey, the cycles in the sky repeat. Let’s track them.
- Greek: The air moves objects through it.
- Greek: Rearranging “atoms” allows motion.
- Greek: Earth, Moon, Sun, move on spheres.
- Greek: Circles are the best! We just need more!
- Greek: A single framework for all geometry.
- Greek: With one little function, I’ll give you the Moon!

**Math can model the universe**

- Greek: Epicycles, equants, eccentricities.
oooh, I like this Dutch spyglass!

Sorry, Aristotle, you're just wrong.

GALILEO GALILEI
1564–1642
Italian

Jupiter has moons, which orbit like our Moon

All bodies on Earth have (circular) inertia
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Galileo, Jupiter’s Moons, “3D” thinking

Notes for & re-productions of Siderius Nuncius
Galileo’s 3D thinking, in WorldWide Telescope

January 11, 1610
preview/diversion...

"Perseus," in WorldWide Telescope (and Aladin, and ESA Sky)
Our Universe is not two-dimensional, but the Sky is.
PERSEUS c. 1918
BLACK & WHITE MONOCHROME IMAGE

Photograph by E. E. Barnard
Figure 2. An Hα image of G159.6-18.5 from Finkbeiner (2003) overlaid on extinction contours derived from 2MASS/NICER (from Ridge et al. 2006a). The Hα image shows the 1.2° diameter diffuse HII region G159.6-18.5 located behind the Perseus molecular cloud and ionized by the O9.5 / B0.5 star HD 278942.

Figure 3. A visual wavelength image of the Perseus molecular cloud. This image was obtained by Adam Block.

Figure 4. The Perseus molecular cloud showing the peak antenna temperature of the 110 GHz J = 1 - 0 transition of 13CO. The circles show Herbig-Haro objects discovered prior to the Mosaic CCD survey of Hα and [SH] emission by Walawender et al. (2005a). The crosses show the new objects found in the Mosaic survey.

Figure 7. IRAS-derived dust column density overlaid with polarization vectors from Goodman et al. (1990). The polarization vectors shown are parallel to the orientation of the magnetic field in the plane of the sky. Blue vectors have polarization strength P > 1.2% and red vectors have P < 1.2%. The stronger polarization may trace warm dust associated with the IRAS dust (courtesy of the COMPLETE team).

All figures reproduced from in Bally et al. 2008, which cites original sources.
Largely thanks to work of the “Astronomical Medicine” project at the Harvard IIC (with Borkin, Halle, Kauffmann et al.)
Diverse High-Dimensional Data

- mm peak (Enoch et al. 2006)
- sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006)
- $^{13}$CO (Ridge et al. 2006)
- mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al.)
- Optical image (Barnard 1927)
Astronomical Medicine

3D Viz made with VolView

INTERACTIVITY

COLOR IMAGE  MARKERS (POINTS)  (OPEN) CONTOURS  ANIMATION  VOLUMETRIC RENDERING

Astronomical Medicine @IIICOMplete
Largely thanks to work of the “Astronomical Medicine” project at the Harvard IIC (with Borkin, Halle, Kauffmann et al.)
3D PDF

Identification algorithms as applied to dendrograms (RA, right ascension; dec., declination). For comparison with the ability of Fig. 1. The 3D visualizations show position–position–velocity (gravitating' leaves labelled with billiard balls are the same as those shown in 64 were proposed as a way to characterize clouds’ hierarchical structure over the range of data cube containing all the significant emission. Dendrogram branches corresponding to self-gravitating objects have been highlighted in yellow over the range of $T_{\text{MB}}$ (main-beam temperature) test-level values for which the virial parameter is less than 2. The $x$–$y$ locations of the four 'self-gravitating' leaves labelled with billiard balls are the same as those shown in Fig. 1. The 3D visualizations show position–position–velocity ($p$–$p$–$v$) space. RA, right ascension; dec., declination. For comparison with the ability of dendrograms (C) to track hierarchical structure, d shows a pseudo-dendrogram of the CLUMPFIND segmentation (b), with the same four labels used in Fig. 1 and in a. As ‘clumps’ are not allowed to belong to larger structures, each pseudo-branch in d is simply a series of lines connecting the maximum emission value in each clump to the threshold value. A very large number of clumps appears in b because of the sensitivity of CLUMPFIND to noise and small-scale structure in the data. In the online PDF version, the 3D cubes (a and b) can be rotated to any orientation, and surfaces can be turned on and off (interaction requires Adobe Acrobat version 7.0.8 or higher). In the printed version, the front face of each 3D cube (the ‘home’ view in the interactive online version) corresponds exactly to the patch of sky shown in Fig. 1, and velocity with respect to the Local Standard of Rest increases from front ($-$5 km s$^{-1}$) to back ($+$8 km s$^{-1}$).

Data, CLUMPFIND typically finds features on a limited range of scales, above but close to the physical resolution of the data, and its results can be overly dependent on input parameters. By tuning CLUMPFIND’s two free parameters, the same molecular-line data set can be used to show either that the frequency distribution of clump mass is the same as the initial mass function of stars or that it follows the much shallower mass function associated with large-scale molecular clouds (Supplementary Fig. 1).

Four years before the advent of CLUMPFIND, ‘structure trees’ were proposed as a way to characterize clouds’ hierarchical structure. With the 3D work as inspiration, we have developed a structure–identification algorithm that allows for the hierarchical structure of a cloud to be easily visualized, as shown in well-developed in other data-intensive applications of tree methodologies so far and almost exclusively within the art of ‘merger trees’ are being used with its interactive online version. The dendrogram shown in Figure 2 and its legend explain the construction of dendrograms schematically. The dendrogram quantifies how and where local maxima of emission merge with each other, and its implementation is possible on paper and 2D screens, we ‘flatten’ the dendrograms of 3D data into a planar curve in two dimensions, and an isosurface in three dimensions, a planar curve in two dimensions, and an isosurface in three dimensions.

The calculation of an observed virial parameter, $x_{\text{MB}} = (2M_{\text{cl}}v_{\text{disp}}^2)/G$, of a set of sources $\left(M_{\text{cl}}, v_{\text{disp}}\right)$, where $x_{\text{MB}} < 2$ (where gravitational energy is comparable to or larger than kinetic energy) correspond to regions of $p$–$p$–$v$ space where self-gravity is significant. As $x_{\text{MB}}$ only represents the ratio of kinetic energy to gravitational energy at one point in time, and does not explicitly capture external over-pressure and/or magnetic field $x_{\text{MB}}$, its measured value likely reflects a ‘cloud’ (i.e. the color and brightness) of any part.
A role for self-gravity at multiple length scales in the process of star formation

Alyssa A. Goodman¹,², Erik W. Rosolowsky²,³, Michelle A. Borkin¹, Jonathan B. Foster², Michael Halle¹,⁴, Jens Kauffmann¹,² & Jaime E. Pineda²

Self-gravity plays a decisive role in the final stages of star formation, where dense cores (size ∼0.1 parsec) inside molecular clouds collapse to form star-plus-disk systems⁴. But self-gravity's role at earlier times (and on larger length scales, such as ∼1 parsec) is unclear; some molecular cloud simulations that do not include self-gravity suggest that ‘turbulent fragmentation’ alone is sufficient to create a mass distribution of dense cores that resembles, and sets, the stellar initial mass function⁵. Here we report a ‘dendrogram’ (hierarchical tree-diagram) analysis that reveals that self-gravity plays a significant role over the full range of possible scales traced by ¹³CO observations in the L1448 molecular cloud, but not everywhere in the observed region. In particular, more than 90 per cent of the compact ‘pre-stellar cores’ traced by peaks of dust emission⁶ are projected on the sky within one of the dendrogram’s self-gravitating ‘leaves’. As these peaks mark the locations of already-forming stars, or of those probably about to form, a self-gravitating cocoon seems a critical condition for their existence.
Linked Views of High-dimensional Data

Statistics

figure, by M. Borkin, reproduced from Goodman 2012, “Principles of High-Dimensional Data Visualization in Astronomy”
Many thanks to Catherine Zucker, Tom Robitaille, Chris Beaumont, Michelle Borkin, Maarten Breddels, Penny Qian, et al.
Linked Views of High-dimensional Data (in Python) 

**glue (and glupyter!)**

video by Tom Robitaille, lead glue developer

**glue created by:** C. Beaumont, M. Borkin, M. Breddels, T. Robitaille, C. Zucker, and A. Goodman, PI
COMPLETE data in glue

+plug-ins, now: OpenSpace & in-prep: ALADiN, esa Sky, yt
More later from Michelle Borkin!
Our Universe is not two-dimensional, but the Sky is.
1D: Columns = “Spectrum”, “Time Series,” “Sequence”
2D: Faces or Slices = “Images,” “Arrays”
3D: Volumes = “3D Renderings”, “2D Movies”
4D: Time Series of Volumes = “3D Movies”
“Astronomy Picture of the Day” for 24 October 2020
Both? Neither? The brain is (well) fooled by the combination motion & occlusion.

Note importance of memory, though…

Dark Matter Pre-Visualization for AMNH “Dark Universe” Space Show
from collaboration of Kaehler, Abel, Emmart, MacLow, Hahn 2014
Note importance of memory, though…

Excerpt from Bialy, Zucker, Goodman, et al. in prep
COLLABORATION

citizen science

shared data

open source, modular, software

collaborative software development

EXPLANATORY VISUALIZATION

combined data sources

plug-in architecture

EXPLORATORY VISUALIZATION

scholarly publication

3D-view exploratory analysis of high-dimensional data
On this page: INTERACTIVES, FIGURES, VIDEOS -- scroll down to see it all.

INTERACTIVES

Explore the RadWave in 3D

- Major cloud catalog
- Local arm fit & masers (Reid+2016)
- Sagittarius arm fit & masers (Reid+21)
- Tenuous connections
- Radcliffe Wave
- Best-fit model
- Possible models
- Gould’s Belt (Perrot & Grenier 2003)
- Click here to TOGGLE unreliable fits
- Sun

The same tools can work for research, teaching & outreach.
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This document is online at tinyurl.com/AGVisIEEE20

Links & Pointers from Alyssa Goodman's IEEE Vis 2020 Talk on "The Past, Present and Future of Visualization in Astronomy"

[Talk slides on iCloud, modulo missing fonts, download for a better experience]

glue: multi-dimensional linked-data exploration

World Wide Telescope, WorldWide Telescope Ambassadors STEM Outreach Program

ADS All-Sky Survey, Aladin, ESA Sky

The Path to Newton, PredictionX

The Timeline Consortium, Aeon Timeline, HarvardX, edX, LabXChange,

OpenSpace, astropy, yt

glue solutions, inc. (consulting)

AR Demos (scan AR codes with mobile device, right-hand code requires a Merge Cube)
“Perseus” Progress
"Perseus" Progress

AEON TIMELINE

[coming soon!]
“Dimension” isn’t even always spatial…

The “3rd” dimension in this 3D plot is “velocity” coming from Doppler Spectroscopy.