YOU CAN TOUCH THESE! CREATING 3D TACTILE REPRESENTATIONS OF HUBBLE SPACE TELESCOPE IMAGES

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Abstract: Astronomical imagery is engaging, inspiring, stimulates public interest, and has proven successful in advancing Science Technology Engineering and Mathematics education. Hubble Space Telescope (HST) discoveries are publicly disseminated routinely through text, images, graphics, visualization, multimedia, social networking and other online mechanisms. To extend these resources to visually impaired individuals and other individuals who could benefit from hands-on physical materials, we created prototype tactile renditions of stunning HST astronomical images on a 3D printer. This paper describes briefly the translation of scientific data from the analysis of HST observations into a format appropriate for 3D printing. Then we describe the resulting tactile 3D prints, outfitted with textures associated with features in a celestial object, specifically using the star-forming region NGC 602 as a prototype. We outline the various textures we adopted and how they were evaluated by several focus groups. We converged on a production and print method and a robust set of textures for blind users and other learners who can benefit from tactile materials. Ultimately a library of these tactile 3D print files can be integrated with a suite of HST educational resources available and distributed through the internet.

Keywords: specialized (visually impaired) students - all levels – astronomy – technology in education - 3D printing - tactile materials

INTRODUCTION

Astronomical images provide a principal source of information that forms public conceptions about space (Snyder, 2011) and can contribute to science, technology, engineering, and mathematics (STEM) education. Historically astronomy originated as a visual science, that is, observation of phenomena emitted in the visible part of the spectrum that could be perceived by the human eye. Even today, the visual presentation of data from all kinds of astronomical observations (not restricted to the visible regime) is an essential part of scientific research. Visual presentations in the form of imagery from data, models, and artist's conceptions serve as communication tools for conveying astrophysics information to the public (Frankel, 2004).

[1] Also European Space Agency, c/o STScI

Astronomy is an engaging subject with broad public appeal, stimulating curiosity about ourselves and the universe.

STEM education is considered critical for U.S. competitiveness and in a very broad sense can contribute to sustainability. Astronomy is relevant for K-12 STEM education and contributes to public science literacy as a whole, although it must be cleverly integrated into the standard U.S. curriculum because it is not always a standard subject in the local classroom. Due to the discipline's public appeal, it makes sense to invoke astronomy to contribute to science literacy (National Science Foundation 2010, International Astronomical Union 2012, and documents from Astronomy U.S. Committee on Science, Technology, Engineering, and Math Education[2]).

Important astronomical discoveries, insights, and breakthroughs are often a direct result of perception and human cognition of the visual presentation of data. However, like all science, the real core of astronomical research is a combination of human characteristics including imagination, perception, inquisitiveness, creativity, perspective, and many other capabilities. Of course, these abilities are not restricted to sighted individuals or persons with particular learning styles. Building skill and expertise in science depends not only on the individual's traits but also on the accessibility of tools, appropriate education, access to current data, research, and training, so the more inclusive science is, the greater is the return to individuals and society. A conscious effort to design, create, and adapt educational resources to meet diverse audience learning needs, researching and implementing innovative techniques, and applying appropriate technologies (c.f., Smith, et al., 2014, Kessler, 2007) can broaden the public access to astronomy. The reward will be engaging the previously untapped intellect of individuals who otherwise routinely encounter barriers in participating in science (Diaz, 2014; Grice, 2012b; Grice, 2010; Beck-Winchatz and Riccobono, 2008).

The authors of this paper, which we call the 3D Astronomy Team, know that astronomy contributes greatly to public understanding, engagement, and education in science. Each member of our team has contributed to a variety of education and outreach programs aimed at diverse target audiences. In particular, for the 3D Astronomy Project described here, we are interested in reaching the visually impaired who are seriously underrepresented in science but have a keen interest in astronomy (Christian et al., 2014; Grice, 2012a; Grice, 2010; Grice et al. , 2004, and *c.f.*, http://astrokit.uv.es). Our 3D Astronomy Team wished to create an authentic, innovative, education/ outreach tactile resource based on real data and printed on a 3D printer. Therefore, we chose to use our own data obtained from the Hubble Space Telescope (HST) on a celestial object we are researching. Since HST imagery has high public appeal and recognition (National Research Council, 2010; NASA, 2014) the experimental 3D printing project described here also can serve as a gateway for producing a library of 3D tactile materials from any HST image when suitably analyzed as we describe in this paper.

In this paper, we specifically describe the first steps of an experimental project to produce 3D tactile renditions of celestial objects for visually impaired and multi-sensory learners. Our aim is to make science more accessible to those audiences using our innovative tactile approach to data representation. Eventually, we desire to distribute our 3D print files through the robust infrastructure provided by STScI. We will use the STScI framework because exemplary HST resources (found online at http://hubblesite.org) are available and understandable through textual materials, imagery, and other elements such as graphics, videos, and computer visualization of astronomical objects and have been distributed for over 20 years to the public (c.f., NASA, 2014) and http://outreachoffice.stsci.edu). However before we can consider introducing such new resources as regular components to be distributed through the extensive public HST HubbleSite infrastructure, we desired to test the suitability and usability of the 3D materials through focus groups. This paper outlines the creation and iterative testing

[2] http://www.whitehouse.gov/administration/eop/ostp/nstc/committees/costem

of the tactile 3D printouts and the potential for utility and distribution of the materials in the future.

UNDERLYING SCIENCE DATA

In all HST education and outreach programs, the essential astrophysics forms the core content for materials made available to diverse audiences and especially in support of STEM education. The scientific expertise of our 3D Astronomy team is centered on the studies of star clusters, that is, groupings of stars that form together and often later dissipate. This topic served as the springboard for the science content for the tactile materials.

Figure 1. A color composite image of the NGC 602 star-forming region created from science observations taken with Hubble Space Telescope's Advanced Camera for Surveys (ACS). North is up and East is to the left. (Courtesy of NASA, ESA. Hubble Heritage and STScI/AURA: http://hubblesite.org/newscenter/archive/releases/2007/04/)

Our prototype cluster for this project is named NGC 602 and is shown in a color composite image (Figure 1). This cluster is located in the wing of a companion galaxy to our own, called the Small Magellanic Cloud and was formed about 5 million years ago (Cignoni, M., 2009). The distance to the object (about 200,000 light years from Earth) is far enough so that the HST Advanced Camera for Surveys (ACS) can observe the entire cluster and surroundings, but close enough that HST can see and measure the brightness of the individual stars. The deep optical observations were taken in 2004 to study the cluster's complex morphology. It has a bubble of gas and dust out of which the cluster was formed, and features in the object, such as stars, gas, and dust can be identified.

As seen in Figure 1, NGC 602 is an ideal target for testing our 3D printing process because it is rich in the following features as noted by Carlson et al (2007):

> *The morphology of the region is reminiscent of a partial ring because the visual image appears as a two-dimensional projection of a ruptured bubble. Two ridges of dust and gaseous filaments outline the nebular shape towards the southeast (lower left in the image) and to the northwest (upper right) and are highlighted by magnificent "elephant trunk" structures. The primary stellar cluster shines in the middle of the broken ring, slightly closer to the southeast ridge. This is where the brightest stars are concentrated. Their winds appear to have swept out the gas and the dust from the center, creating the inner cavity of the bubble. Many faint stars are visible on, or in close proximity to, the two ridges, indicating that star formation is still active there.*

All of these attributes can be appreciated in the HST image through visual examination. Our challenge was to represent this same information in a tactile format.

In addition to graphically documenting the appearance of the composite NGC 602 HST image, we measured the individual HST observations to determine the brightness of each feature seen in the image. Measurement of the individual HST frames allows us to calculate the flux in each wavelength, whereas the intensities in the one composite image are enhanced during image processing to make a better color image presentation, and therefore do not represent an absolute scaling of the physical radiation output from each feature. The outer contour of each individual feature was determined, and then the area within the contour was measured for intensity and used to populate a data cube. The components of the data cube are: an X-Y position, a feature type (stars, gas, dust, and filaments), a measured intensity, and a Z-distance from the observer. As a result, the cluster's physical attributes were all codified--the brightness and the position of all the stars, and the relative intensity and the position of the dust and gaseous regions. The HST observations were augmented with information from the literature, thus being able to further infer the locations where dust and gas are primarily concentrated. We measured the size of the surrounding bubble and estimated its thickness. Ultimately, for the purpose of transforming the scientific measurements into information appropriate for 3D printing, we consolidated all data into three key concepts to convey:

- The overall structure of NGC602 is spherical.
- There is a very bright stellar cluster near the center.
- There are extended regions of gas and dust, for which we had measured the relative intensities.

TRANSFORMATION OF SCIENCE DATA TO 3D PRINT FORMAT

The data cube described above provided the locations and intensities of all the features in the image. This data had to be transformed into a format suitable for 3D printing. Two versions of the data cube were created: first, a file representing the feature locations of the nebula, each with a unique texture (we called this the composite "*texture map*", c.f., Figures 2 and 3a) and second, a file with the measured light intensities for each feature presented as variations or undulations in the surface height or "elevation" of the texture map (called the composite "*elevation map*" *c.f.*, Figure 3b). Therefore the 3D prints represent each type of feature in the HST image in Figure 1 with a unique texture, providing a tactile analog to the visual image that shows NGC 602 as a composite of unique colors and intensities. The *texture* and *elevation maps* are the first steps towards our longer-term objectives which include representing the full 3D structure of the object in a variety of ways – a series of 3D prints organized in individual planes representing different distances, a 3D printout that can be assembled easily into a 3D object, or digital representations integrated with other methods and technologies we are considering which are beyond the scope of this paper.

The transformation of scientific data to a format for 3D printing is not trivial, and the process we developed was a significant part of the 3D Astronomy project. Once the scientific analysis and measurement of the NGC 602 HST observations was complete, we re-sampled, smoothed, and interpolated the data to obtain a reasonable portrayal of NGC 602 that had to be converted into the file format appropriate for 3D printers. Specifically, 3D printers expect the STereoLithography (STL) file format[3], commonly used in Computer Aided Design (CAD) programs and 3-D animation rendering programs, such as Blender. Unfortunately, none of those current types of software handle astronomical data gracefully. Also, the programs are not able to ingest cubes of data from any numerical scientific analysis or technical measurements. Therefore we processed the smoothed data using in-house developed scripts and programs to produce a format that the commercial software packages mentioned above could handle. Many commercial packages are able to export the data in the STL format if the input data is in the

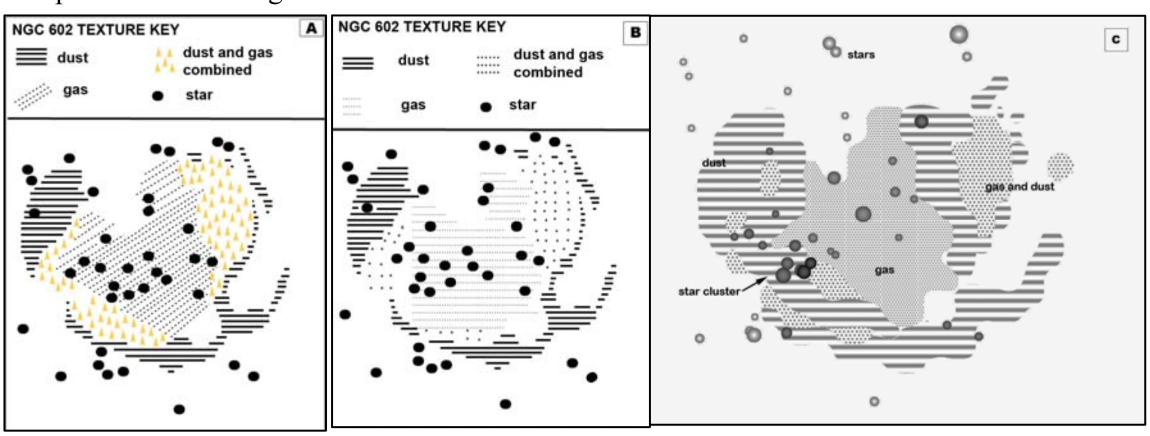
[3] http://www.3dsystems.com/quickparts/learning-center/what-is-stl-file

form of grids, meshes, or CAD-like files. The advantage of using STL files is to enable the printing of the tactile materials by anyone with access to low-end affordable printers as well as to high-end exhibit quality devices. Thus an important outcome of this project is that we cannot use a hand-tuned, human-intensive process, but rather, we will need to create a pipeline to allow us to annotate and measure an image, convert the data to suitable file formats, and then transform those files appropriately, in order to process numerous HST images and create a library of STL files for the public.

TEXTURES

Considerable experience has been gained in representing astronomical data with textures to convey information to the visually impaired, c.f., Grice (2012). Before we decided on specific textures to use for 3D printing, we also investigated the literature regarding different learning styles, primarily focusing on sighted and blind individuals (e.g., Dion, Hoffman and Matter (2000); Braille Authority of North America (2011)). Other journals we found useful that contained articles as well as other online reference materials include the *Journal of Visual Impairment and Blindness* (http://www.afb.org/info/publications/jvib/), the *Journal of Blindness Innovation and Research*, and the *A to Z of Brain, Mind and Learning*.

Our testing sessions, described below, were aimed at evaluating the textures and the usability of the printed products. Over time we have learned, through observation of individuals examining displays of HST images, that when some sighted individuals look at an image, they might take in the whole image first, and then examine the finer detail, especially if prompted by textual, hyper-text, or audio guidance. In contrast, some blind and visually impaired learners examine details and then use their “mind’s eye” to combine these parts to create the whole image. We had to accommodate both approaches with our materials by providing tactile legends for the textures, and aural guides to the nature of the astronomical object being depicted. We found that assisting the ability of individuals to distinguish small details can be critical in understanding complex situations depicted in images, so this had to be a key component of our design.



Figures 2a,b,c. Textures used for testing. a) Initial textures used for Swell Form and small format 3D prints, tested at the NFB 2013 Orlando conference and the STEMX conference. The slanted lines used for gas were less identifiable than other textures on the 3D prints. b) Revised textures for the Connecticut NFB Chapter and Maryland NFB State Convention tests. The gas pattern, although somewhat distinguishable, was thought to be “non intuitive” by some testers. c) Current set of textures being used in informal testing scenarios (not formalized meetings or conventions). The textures for the gas and the gas + dust combination are similar stipple patterns, but the gas texture is much smoother and “softer”, while the gas=dust pattern is rougher and more evocative of that feature.

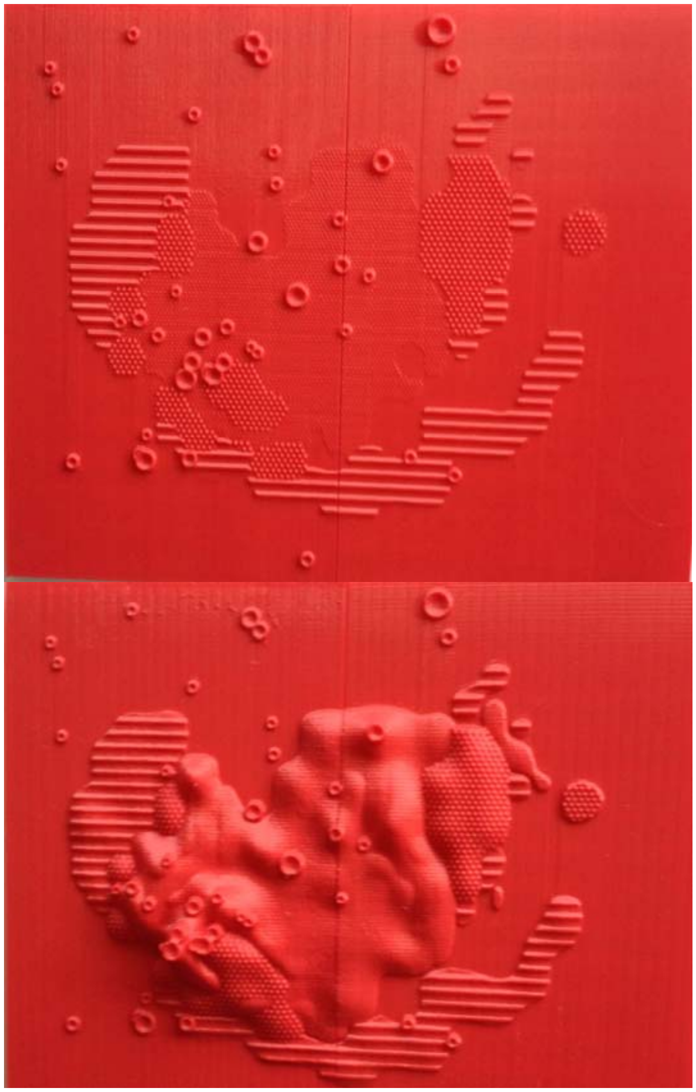


Figure 3. Texture and elevation 3D print maps (large format) of the star cluster NGC 602 from HST data. These maps were tested at the CT and MD NFB State Conventions in November 2013.

Before we started using the 3D printer, we created template textures on Swell Form prints (thermal expansion paper where darkened areas of the paper “puff” and become tactile when heated in a Swell Form machine, see Figure 2a,b,c,; note that NFB means National Federation of the Blind). This step in our project demonstrated that the Swell Form paper technology was useful in introducing various textures to visually impaired individuals, especially those familiar with Braille, and aided them in distinguishing different patterns, in preparation for examining 3D solid prints. Also the Swell Form prints are much faster to produce, so iteration of textures could be accomplished quickly.

After lengthy examination and tuning of the print process, as well as matching the resolution, file size, and other characteristics to our specific printer, we printed 3D composite *texture* and *elevation* maps for NGC 602, using the textures shown in Figure 2a, then revised as based on testing to those in Figure 2b, and finally those in 2c.

EVALUATION PLAN

Before our 3D materials can be integrated into any robust education or outreach program, we desired to investigate if our development process produced 3D materials that were actually usable and understandable. We developed a method for evaluating the materials and engaged a series of focus groups to assess the materials. The feedback from the groups provided input for modifying both our process and the materials each step of the way.

Evaluation Plan

Our procedure for the testing of materials was organized by asking participants to:

- Examine a visual image, if the user had partial vision,
- Listen to a description read aloud before experiencing the textured materials,
- Examine the Swell Form paper textured image and the legend to introduce the textures (note that after the first two focus groups, this step was recommended as unnecessary by the subsequent focus groups),
- Examine the 3D prints and compare with a single composite Swell Form illustration,
- Compare *texture* and *elevation* maps,
- Respond to a survey to assess user responses to the textures and understanding of the features of the NGC 602 image.

Instrument

We designed a suite of survey questions to probe the participants' specific understanding of the textures and preliminary familiarization with the printout formats, and to obtain some free form feedback (Appendix). Basically, participants were asked:

- If they could identify each of the features (stars, gas, dust, combination) on both the Swell Form (eliminated after the second focus group) and the 3D printouts,
- If they began to understand the Nature of NGC 602 from the 3D printouts by, for example, verbally describing the structure and the spatial relationship between the star cluster, the gas, the dust and the overall extension of the cluster system.
- How they would improve both the Swell Form and the 3D printouts.

FOCUS GROUP RESULTS

First Iteration - Focus Groups

Testing results are summarized in Table 1. For the very first set of prints, we used a half-sized print on the 3D printer because 3D printing is very time consuming (several hours), and we had early opportunities to have our materials examined by focus groups. The first two groups of testers used materials with the textures demonstrated in Figure 2a. One group attended the 2013 National Federation of the Blind Convention (NFB) in Orlando, and the second group attended the 2013 NFB STEM-X Resource Fair in Maryland aimed at high school students.

At the NFB convention, 15 blind and visually impaired individuals with a range of ages (20-68 yrs) who were participants at a Science and Technology Division meeting volunteered as testers. The background and professions of the individuals in the division made it easy for them to understand the project idea and basic concepts for the testing. Several individuals were fami-

Table 1
Summary of testing and surveys of NGC 602 Tactile Materials

Venue	Testers characteristics	Materials	Survey Responses	Open Feedback
NFB Convention Orlando, FL Early July, 2013	15 individuals, 20-68 years of age. HS - PhD. One college student-- Physics and Astronomy; One PhD in Astronomy. ~50% with prior tactile/3D materials experience.	Textual description (read aloud). Visual image (for sighted participants). Swell Form composite (8.5 x 11 inches). *Texture* map (small format). *Elevation* map (small format).	Swell Form Textures identifiable by 100%. 3D map textures: stars identifiable by 100%. Other features identifiable by half the participants, - gas+dust most difficult. Gas (dotted slant lines). Dust (horizontal lines). Gas+Dust (triangles). Swell Form helped understand 3D print.	3D map textures harder to discern. Regions should have clear boundaries. 3D map size does not match Swell Form and is too small. Color for individuals with partial vision would be helpful.
NFB STEM-X Towson, MD late July 2013	22 individuals. 12 boys, 10 girls, 14-18+ years of age. High school. At least 13 with tactile experience and 3D, 5 with neither.	Textual description (read aloud). Visual image (for sighted participants). Individual Swell Forms for each feature (gas, dust, stars, etc.). Swell Form composite (8.5 x 11 inches). *Texture* map (small format). *Elevation* map (small format).	Stars (circles) easiest to identify. Dust (horizontal lines) by half the participants. Gas (dotted slant lines) and gas+dust combination (triangles) least identifiable. Composite and individual Swell Forms helped understand concepts and 3D print textures.	3D maps too small. Regions need to have clear boundaries or edges. Put a texture key near or on the 3D printout. Use color if possible.
NFB State Convention Connecticut Early November 2013	11 individuals. Adults.	Textual description (read aloud). Visual image (for sighted participants). Textures 3D legend. *Texture* 3D map (large format). *Elevation* 3D map (large format).	Stars (circles) easiest to identify on both maps. Dust (horizontal lines) identifiable on both maps by 100%. Gas (soft stipple pattern) identifiable on both maps by 9 individuals. Gas+dust combination (wide stipple) identifiable by 100%.	Features "easier to distinguish" – some preferred *elevation* map, some *texture* map, some had no preference. 100% could identify brightest features on elevation model Some liked both *texture* and *elevation* to build mental model of cluster.
NFB State Convention Maryland Late November 2013	40 individuals. 10-81 years of age. Grade school through PhD. Some with science backgrounds. Some teachers. Widely varied experience with Braille. Some with 3D tactile experience.	Textual description (read aloud). Visual image (for sighted participants). Textures 3D legend. Texture 3D map (large format). Elevation 3D map (large format).	Stars (circles) easiest to identify on both maps. Dust (horizontal lines) identifiable on both maps by 100%. Gas (soft stipple pattern) identifiable on both maps by most. Gas+dust combination (wide stipple) identifiable by all but 2 individuals.	Features: Easy to distinguish for most, preferred legend *on* prints, not separate. Dust horizontal-line texture was "non-intuitive" but distinguishable. 100% could identify brightest features on elevation model. Prior Braille or tactile experience: most felt comfortable using legend and elevations. Less Braille or tactile experience: Some liked both texture and elevation.

-liar with astronomy. Many but not all of the participants had experience with tactile materials. Generally, participants could identify the circular symbols depicting stars on all materials. The dust and gas features, represented respectively by thick horizontal lines and slanted dotted lines, were identifiable on the Swell Form, but less than half of the participants perceived them easily on either the 3D printed *texture* or *elevation* maps. The gas plus dust combination, represented by triangles, was more problematic as 75% of the testers could identify the texture on Swell Form but only 30% on either 3D printout. The *elevation* maps received mixed reviews – but participants did understand that the elevation represented brightness and could distinguish what features were dominant. Participants appreciated using the Swell Form as a starting point. However much of the problem with the textures was ultimately traced to the fact that our initial 3D prints were half the size of the Swell Form piece of paper, thus severely limiting usability.

At the STEM-X event, there were 20 high school students who participated in the evaluation. STEM-X is a program offering opportunities for inquiry-based learning, so this audience was already interested in science. At this initial stage, interacting with a somewhat science literate audience was helpful so that we could concentrate on the texture and printout evaluation rather than "teaching astronomy" *per se*. The materials used by the high school students were slightly different than for the Convention group as a result of that first group's feedback. Rather than having evaluators compare the 3D prints to a single composite Swell Form page, the image was deconstructed into a series of individual Swell Form pages, to better familiarize the testers to each unique texture. In this evaluation, successive Swell Form images represented an individual texture, culminating with the composite image. This strategy greatly helped the participants to distinguish individual features on the combined Swell Form and 3D print materials. Nevertheless, it appeared the small format of the half-sized 3D prints caused most of the difficulty with the *texture* and *elevation* maps.

The major results were that, while enthusiastic about the concept of the 3D prints, both groups made it clear that a size similar to an 8x11-inch piece of paper would be more appropriate to use, and would nicely match the Swell Form illustrations. Also, using slanted and horizontal lines in the same print in our first textures (seen in Figure 2a) was considered too confusing. As a result of this feedback and before we generated a larger set of prints (which take 12-15 hours to produce), we made test pieces with various roughness' and texture spacings as well as design elements such as pattern heights, thicknesses, and textures relative to the substrate. These objects were examined informally by various individuals mostly associated with local NFB chapter members who were keen to have an opportunity to provide feedback. We also found that larger prints had to be produced in pieces because the printer stage was too small to fabricate the desired (approximately 8x11-inch) size. This is relevant for any individual who wishes to print these on their own, or in large quantities, as some assembly is required before use.

Second Iteration -Focus Groups

We tested the 3D *texture* and *elevation* maps at the 2013 NFB Connecticut and Maryland State Conventions using nearly the same procedure as the initial testing, and results are also presented in Table 1. The new textures (Figure 2b and Figure 3) symbolized stars as circles with an indentation resembling a tiny bowl, to distinguish them from other raised patterns. Gas was represented as a dotted pattern and dust as horizontal lines, while the dust + gas combination was a roughened dotted texture. We included a 3D-printed tactile legend separately from the maps, and this seemed to help greatly by eliminating the necessity (according to the participants) of using the Swell Form illustrations as a texture introduction. Participants examined the legend and *texture* map to gain familiarity with the shape and overall composition of NGC 602's features, and reported whether they could locate and distinguish stars, gas and dust. The 3D *elevation* map was examined by each person subsequently, and then they answered the survey questions. The participants in Connecticut decided immediately that they did not need to use the Swell Form print at all so we quickly abandoned its use. Since the new 3D printouts were larger format and higher resolution, the users felt that the *texture* map was redundant to, and with more distinctive textures, than the Swell Form.

The Connecticut test group consisted of 11 people who were born blind, or somewhat visually impaired, and a number of people who lost their sight later in life. Nearly 100% of the participants easily identified textures on the *texture* map 3D printout. Most people could also identify the areas on the *elevation* model. For this test group, we found that participants who lost their sight later in life preferred the flat *texture* map, or preferred to use it before the *elevation* map, and thought the texture for gas was harder to find in the elevated model. Conversely, participants who were tactile readers throughout their life often preferred the *elevation* model, and remarked that in the future they would not need a *texture* map. All agreed that having both versions of the tactile material offered non-visual access to the broadest audience.

The Maryland test group included a few staff from the National Federation of the Blind headquarters. This small subset of participants had more experience using tactile graphics and often chose the elevated model as their favorite. A total of 40 participants were surveyed at the Maryland Convention, and were a range of ages (from 10 to 81 years) with a wide range of backgrounds, some with science, technical, and teaching backgrounds, and others from other professions. In addition to asking survey questions, we videotaped the interviews with participants to get their impressions.

ANALYSIS

The results from the focus groups indicated that once we produced larger format 3D prints and improved textures, nearly all participants could find textures on the *texture* map and nearly everyone could identify the textures on the *elevation* map as well. As mentioned above, individuals who had been blind from birth, or for a very long time, tended to be more familiar with Braille and had more experience with tactile materials, and therefore preferred to use the *elevation* model at the outset. Other individuals felt that the legend, the *texture* map, and the *elevation* map were most useful when used in sequence. Also, interestingly, those very familiar with tactile materials thought that "others with less experience" would benefit from the legend and *texture* maps. These skilled individuals had spent time in the company of people who needed some mentoring with tactile materials, so they were able to see the value of the progressive use of more complex materials.

Most Maryland respondents provided numerous additional comments and suggestions. Regarding the textures, a common comment was that the texture for the dust should be more intuitive and evocative (horizontal lines were hard to understand and remember, and did not evoke the mental image for "dust"). The testers felt the tight rougher triangular pattern was appropriate for the dust. The gas pattern was softer, and the respondents reacted favorably to its texture. Participants also felt that the texture used for the gas+dust regions should be similar to the dust but somehow also remind them of the gas. The current textures we are using, demonstrating, and informally testing reflect this input (Figure 3**)** see also https://sites.google.com/site/3dastronomy/). Creating textures that are evocative of the physical features apparently assists in stimulating, building, and reinforcing a person's mental model of the NGC 602 cluster region. Participants reported that the *elevation* map did help them understand the star cluster structure, and some individuals remarked they could "see" the cluster, a remarkable outcome .

Some participants in the Maryland group reinforced our idea that tactile materials could assist all kinds of learners. In particular, several parents and teachers remarked that the materials would be especially useful for students on the autistic spectrum, and also the home schooled. We definitely would like to broaden the applicability of the 3D materials to many groups as our project matures, and when we are able to provide a library of printable files to the public.

SUMMARY AND FUTURE WORK

Summary

We have demonstrated and tested the results of the first step in a new process for converting visual imagery and associated scientific data from Hubble Space Telescope observations to 3D tactile print products. From scientific analysis of HST data, we created tactile 3D printouts mapping the features of the celestial star-forming region, NGC 602, into textures. We tested suites of textures printed with a low cost 3D printer (a Makerbot Replicator 2) to determine which textures were most distinguishable, most useable, and feasible to print either as a flat textured image representation, that is, a *texture* map, or as undulating surfaces in an *elevation* map, representing NGC 602 features and light intensity from those textures or elevations**.** We found that a sequence of print materials--a tactile legend, a *texture* map and an *elevation* map used in succession--provides information to visually impaired individuals and can well convey the key elements of the HST imagery. The printouts helped the participants build a mental model of the star formation region being depicted.

These 3D prints will be of use to the visually impaired, and generally to anyone who finds tactile materials useful for understanding astronomy. We envision that the printouts can be used as primary materials for presenting astrophysical concepts to learners who can make use of tactile materials, supplemental resources for news releases through internet distribution of the 3D print files for printing by the user, as materials that can augment informal science displays of astronomical information, exhibits and planetarium shows, and as supplemental materials for science classes covering astronomical and science topics. Home schooling parents we interviewed suggested they would use these materials, especially if they can print objects at home. Others with special needs or autistic students that respond to tactile materials may use these to augment their instructional tools.

Limitations

During the course of this project, we found that producing 3D tactile representations of HST data for astronomical objects necessitated the use of existing software augmented with hand-tuning and custom algorithms. The CAD-type programs such as MeshLab, Google Sketchup, Tinkercad and others (http://www.3ders.org/3d-software/3d-software-list.html) suitable for production of 3D print materials can be used to represent physical objects in digital space and then print them, but they are not set up to ingest our kind of numerical data (indeed, as far as we know there is *no* CAD program that will ingest a spreadsheet). Also, although most 3D printers use the same file format, even in industry, there are specific methods and procedures that pertain to each of the types of printer being used. Print order and object orientation on the printer are important, but this is a complex issue highly dependent upon the design, printer, structure and plastic and sometimes 3D printouts need to be hand polished, painted and otherwise treated after production.

In our case, because we use a low-end printer that could be a typical device used in schools, libraries, museums, and for home use, we placed importance on experimenting with printing test pieces to assess surface quality, and accuracy. The low-end printer is not capable of the highest resolution one might desire, and other nuances arose, such as the roughness and uniformity of textures being a function of the orientation of the print piece on the printer bed, among others.

Next Steps

Our initial process for translating HST images and science measurements into 3D prints has been successful, producing materials that are usable and understandable by the visually-impaired and other tactile learners. We are currently tuning the process so that it will be possible to offer 3D print files to the public as part of the regular production of public imagery from HST. Our goal is to produce a library of such files for printing by anyone.

To utilize additional scientific data on other star clusters and celestial objects, we intend to improve the data ingest method so that scientists producing imagery and associated measurements can manipulate their data into the appropriate file formats for 3D printing. This will involve a custom interface for scientists, and a translation mechanism from that interface and science data to a program that can produce 3D print files. We will still target the lower end 3D printers as they will be more widely available to the public and educators. Eventually when we are satisfied with resolution and accuracy, we can produce test prints for higher end devices to create 3D exhibit quality products. We foresee that 3D science data from HST researchers will be useful not only for 3D printers, but also for internet 3D renditions as well as new emerging technologies such as gesture technologies (with/without gloves), heads-up technology, and others.

The next phase of 3D tactile representation development is to create distance layers, mimicking a visual fly-through from near to far, or to create a physical object that an individual can hold an accurate representation of a celestial object in their hands. The real challenge is not only to transform the scientific measurements and graphical information into a format for the printer, but also impose uniform, clear textures on curving, undulating surfaces. When we achieve production success, we will be in a good position to broaden 3D Astronomy printing and integrate these products into learning modules for both formal and informal education. As well, we will be able to create a library of STL files of HST data for use by anyone

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APPENDIX

SURVEY QUESTIONS FOR FOCUS GROUPS

Relevant Survey Questions (Tests 1 and 2- NFB Orlando National Convention and MD NFB STEM-X):

The visual image was made available to the participants and a verbal description of NGC 602 was provided to the participants before each individual examined the materials and responded to the survey.

1. Can you locate the circular star symbols in the tactile graphic (Swell Form) and in the 3D maps?

2. Can you locate the dust texture (thick horizontal lines) in the tactile graphic (Swell Form) and in the 3D maps?

3. Can you locate the combined dust and gas (triangle) texture in the tactile graphic (Swell Form) and in the 3D maps?

4. Can you locate the gas texture (slanted dotted lines) in the tactile graphic (Swell Form) and in the 3D maps?

5. Does examining the tactile graphic (Swell Form) help you better understand the 3D maps?

6. How would you improve the tactile graphic – Swell Form?

7. How would you improve the 3D maps?

8. If you are low vision or sighted, does examining the color image of NGC 602 help you to better understand the tactile graphic and 3D model?

9. Does examining the tactile graphic (Swell Form) help you understand the 3D maps?

10. What is your experience using tactile graphics and/or 3D models?

11. Any questions or comments for the tactile designers?

12. What is your age and highest degree of education/occupation?

Relevant Survey Questions (Tests 3 and 4 – CT and MD NFB State Conventions)

The visual image was made available to the participants and a verbal description of NGC 602 was provided to the participants before each individual examined the materials and responded to the survey.

Please use the tactile texture key first so you are familiar with the textures.
Please answer the following questions. Comments are welcome at any time.

1. Do you have any experience with Braille or tactile materials?
2. Can you find the circular star symbols in the *texture* map? In the *elevation* map?
3. Can you find the dust texture (horizontal lines) in the *texture* map? In the *elevation* map?
4. Can you locate the soft gas texture in the *texture* map? In the *elevation* map?
5. Can you find the combined dust and gas (rough) texture in the *texture* map? In the *elevation* map?
6. Are the different textures harder or easier to identify on the *elevation* map as compared with the *texture* map? Why?
7. Can you detect by touch, any difference in brightness (energy output) of the different features on the *elevation* map?
8. Which particular features do you think are the brightest/most intense on the *elevation* map?
9. How would you describe the strengths and weaknesses of each tactile map of NGC 602?