What Determines the Aesthetic Appeal of Astronomical Images?

Lars Lindberg Christensen
European Southern Observatory
lars@eso.org

Douglas Pierce-Price
European Southern Observatory
dpiercep@eso.org

Olivier Hainaut
European Southern Observatory
ohainaut@eso.org

Keywords
Astronomical Images, Astrophotography, Photography, Image Processing

Summary

In the context of images used for education and outreach purposes, this paper describes a set of parameters that are key in determining the aesthetic appeal, or beauty, of an astronomical image.

Rationale

The importance of images in the public communication of astronomy can hardly be overstated. Images are not just a means of visual communication. They can inspire awe, wonder and enthusiasm, and portray the Universe as a fascinating place worthy of exploration. Producing engaging astronomical images with aesthetic appeal or beauty is, thus, an important objective for astronomical communicators. If we can determine the parameters that influence how well an image is received by the viewer, it becomes easier (and potentially faster) to produce higher quality images and it becomes possible for a wider range of people and observatories to produce them.

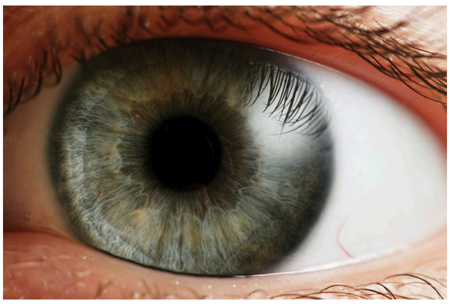

Figure 1. The human eye — one of the most complex creations of nature. Credit: Petr Novák (under Creative Commons via Wikipedia).

Introduction

The human eye (Figure 1) is one of the most complex creations of nature. With its intricate system of sensory cells — light-sensitive rods and colour-sensitive cones — we experience the world around us visually. But what determines whether we enjoy looking at an image or not? Specifically what determines whether we enjoy looking at astronomical images like the ones shown in Figure 2?

The problem of trying to describe beautiful images in a logical manner is not isolated to astronomy. One of the holy grails of computer graphics science is the algorithmic description of beauty in self-similar life forms, for example, as pioneered by Prusinkiewicz & Lindenmayer in their book *The Algorithmic Beauty of Plants* (1990). The aim here is to define the algorithmic beauty of a plant by reducing it to a series of interacting components (see Figure 3).

Based on the experience of composing almost 1000 outreach images from raw data from ESO's telescopes and the NASA/ESA Hubble Space Telescope, in this paper, we propose that six parameters, described in the sections below, are key in determining the aesthetic appeal of an astronomical colour image. These are photogenic resolution, definition (or structure or contrast), colour, composition, signal-to-noise ratio, and how well instrumental artefacts have been removed.

In this paper, we do not discuss the details of producing the final colour outreach images from multiple datasets. In essence, this involves astronomical processing on high dynamic range[1] FITS files, dynamic range compression of the processed files, and final composition and graphical processing to reach the end result of a low dynamic range, publication-ready colour image. An example of a tool for the most sensitive parts of this process is the ESA/ESO/NASA FITS Liberator software. The documentation on this program's website[2] includes a short introduction to astronomical image processing[3] and a step-by-step guide to making images[4]. Other texts on the production of astronomical colour images are Rector *et al.* (2007), Christensen (2007), and sources referenced therein.

Figure 2. *Collage of beautiful astronomical images from small and large telescopes on the ground and in space — such as the Gemini Observatory, ESO's Very Large Telescope, Chandra X-Ray Observatory, ALMA, the NASA/ESA Hubble Space Telescope, NASA's Spitzer Space Telescope, ESO's Visible and Infrared Survey Telescope for Astronomy (VISTA) and ESO's VLT Survey Telescope (VST). These images serve as inspiration for many and are a stark reminder that our existence here on Earth is just a small cross-section of the many different environments that exist in the Universe.*

1. Photogenic resolution

Early marketing for consumer digital cameras often concentrated on the total number of pixels in the detector, and hence in the resultant photographs. A larger number of "megapixels" is often considered to be an indicator of a better camera. However, in real life there are other limiting technical factors such as the quality of the camera's optics. This is also true in the case of astronomical observations: a key factor is the angular resolution of the observation, which, for a diffraction-limited single-aperture telescope, is improved by increasing the diameter of the telescope's primary mirror, but not by increasing the number of pixels in the detector. And since astronomers use big "zoom lenses", another limiting factor for astronomical images at visible wavelengths is the atmospheric blurring of images. A phenomenon that manifests itself in the twinkling of stars at night due to atmospheric scattering or the flickering of distant objects in the daytime due to heat haze.

So, a large number of pixels alone is not a guarantee of sharpness — the photo may simply be oversampled, i.e., have much more finely spaced pixels than are needed to display the smallest features that are actually resolved. A many-megapixel image of a blurred object is still blurred. Furthermore, an image with excellent sharpness may not be visually appealing if a narrow field of view means that there are not many features in the picture. Therefore, to be more precise, the real factor that limits the aesthetics of an image is the photogenic resolution, r_{photo} — the number of effective resolution elements (the size of the finest feature that can be resolved) across the field of view (FOV):

Figure 3. *Artificial trees generated by biological modelling and visualisation algorithms embedded in the TreeSketch iPad software. Credit: Steven Longay*

$$r_{photo} = \mathrm{FOV}/\theta_{effective},$$

where $\theta_{effective}$ is the effective angular resolution. For an astronomical image, one can view this in simple terms as the greatest number of stars (considered to be point sources) that can fit side by side across the field of view. In the ideal case, where the optics are perfect and there is no atmospheric distortion, the diffraction-limited angular resolution $\theta_{diffraction}$ for a single-aperture telescope is approximated by:

$$\theta_{diffraction} = \lambda/D,$$

where D is the diameter of the primary mirror or lens and λ is the wavelength observed. As mentioned, however, the real resolution — at visible wavelengths at least — is most often limited by the atmospheric quality, or seeing. In reality, this usually limits the effective resolution of any telescope to that achieved by a 30-centimetre telescope, such as those used by advanced amateur astronomers.

In our experience, for an image to look impressive, the photogenic resolution should be greater than of order 1000. For instance, the MPG/ESO 2.2-metre telescope's Wide Field Imager (2.2-metre/WFI) can produce individual images with $r_{photo} > 2000$, as can the Wide Field Channel of Hubble's Advanced Camera for Surveys (HST/ACS-WFC). Images with rphoto << 1000 will inevitably look blurred. If an individual observation has a low photogenic resolution (due to low

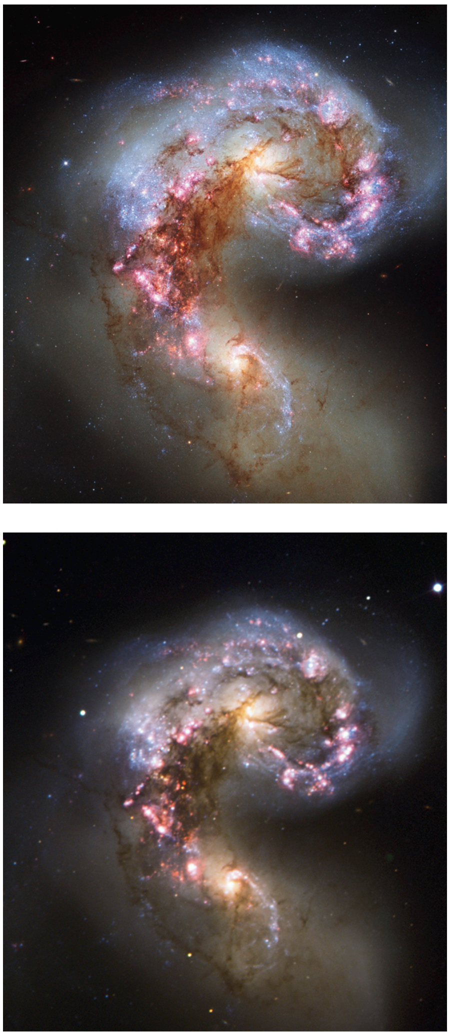

Figure 4. Comparing the effective angular resolution of Hubble (top) with that of the VLT's ground-based 8-metre telescope (bottom). As Hubble's optics are very good, and there is no atmosphere disturbing the resolution of the image, their picture is limited only by the wave nature of light itself and the diameter of the primary mirror. The VLT image suffers from atmospheric distortion and is oversampled (has fewer effective resolution elements). Credit: NASA & ESA/ Hubble, European Southern Observatory

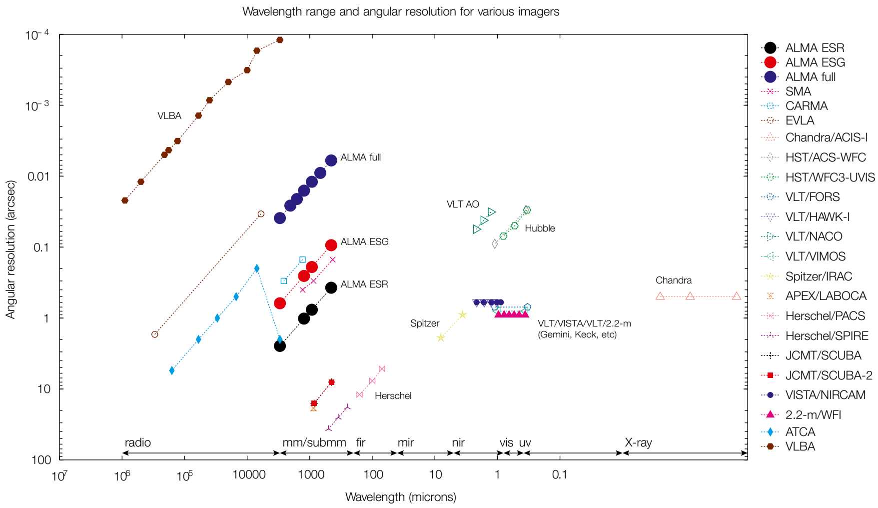

Figure 5. Wavelength range and effective angular resolution for a small selection of different astronomical telescopes and imagers.

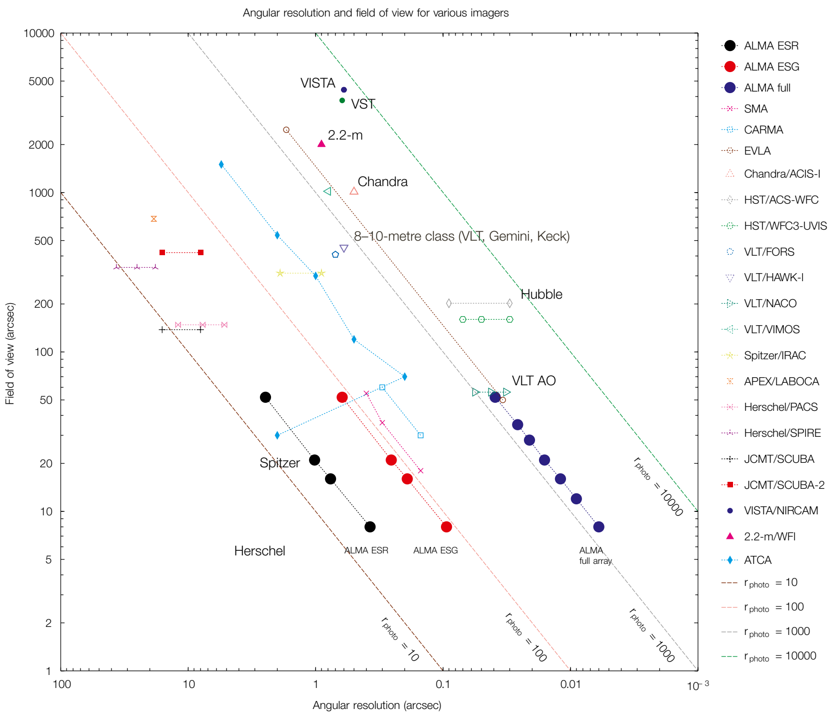

Figure 6. Effective angular resolution plotted against the field of view for a selection of different imagers.

angular resolution, narrow field of view, or both), a mosaic of multiple observations can improve the resulting photogenic resolution. Advanced hobby astronomers often do this and achieve very impressive images — sometimes even outperforming images from professional telescopes.

If we plot the effective angular resolution, $\theta_{effective}$, for different astronomical telescopes and imagers against the wavelength region they work in, we get Figure 5 (Pierce-Price *et al.*, 2011). The optical telescopes all cluster in the same region because the atmospheric seeing — without the use of adaptive optics — restricts their effective angular resolution to around 0.5 arcseconds. To the left of the visible wavelength area is the longer-wavelength radio regime. In particular, the submillimetre part of the spectrum is of great interest at present, as the Atacama Large Millimeter/submillimeter Array (ALMA) has recently begun operating and is revolutionising observations in this wavelength range[6]. ALMA's initial specifications for first observations with a partial array are plotted (ALMA ES, for Early Science) in addition to the resolution achievable with the full array (ALMA full). An interesting comparison is also apparent between Hubble and ground-based 8-metre-class telescopes without adaptive optics (AO). Also plotted is the performance of 8-metre-class telescopes applying AO, such as the VLT, Gemini or Keck: they are very similar to Hubble in terms of resolution, but work in slightly different wavelength regimes (as AO works in the near-infrared).

Although the figure is interesting in its own right, it is more insightful for our purposes to examine the photogenic resolution by plotting the field of view against the effective angular resolution (Figure 6; Pierce-Price *et al.,* 2011). In this plot, lines of constant photogenic resolution form diagonal lines, and examples are shown from r_{photo} = 10 (lower left) to 10 000 (upper right).

Few, or possibly none, of the current imagers deliver a native photogenic resolution of more than 10 000, but this resolution is likely to be achieved with new giga-imagers such as the Pan-STARRS camera (5 gigapixels). It is also interesting that the domain of photogenic resolution between 1000 and 10 000, which, for many years, has been dominated by Hubble, now has several players, such as Chandra, the MPG/ESO 2.2-metre telescope, the Canada France Hawaii Telescope (CFHT), ESO's VISTA and VST telescopes and soon, to some degree, ALMA in its full configuration.

2. Definition

Even if an image has a very high photogenic resolution, its content is still the most important factor. The frame of the image needs to be filled with an object of interesting structure, such as a galaxy or a nebula. And definition or contrast in the interesting parts of that object is our second key parameter in the aesthetic appeal of an astronomical image.

The definition is fixed in the representation of the dynamic range, defined as the ratio between the maximum and minimum values of a physical measurement[7]. The definition is adjusted during image processing, where the original high dynamic range FITS data[8] are mapped to the (often more limited) range of pixel values that can be shown in the outreach image. This is done with the help of a stretch function. The choice of stretch function to reach a good contrast depends greatly on the difference in brightness between the different interesting parts of the images. Typically, a galaxy will need a highly non-linear stretch to reach a good contrast, because of the high dynamic range between the bright centre and the fainter outer areas. However, a nebula will need less stretch (or even a linear stretch) because of the lower dynamic range between the nebulous components and the other interesting parts of the image. Without adjusting the dynamic range, most astronomical images would just show some saturated highlights in a very dark image (see Figure 8), similar to taking a portrait against a background sunset.

Figure 7. Carina Nebula taken with the VST, which delivers a Hubble-level photogenic resolution of 5500. Like those from Hubble, the VST image appears sharp and rich in information, with a high aesthetic appeal. Credit: ESO

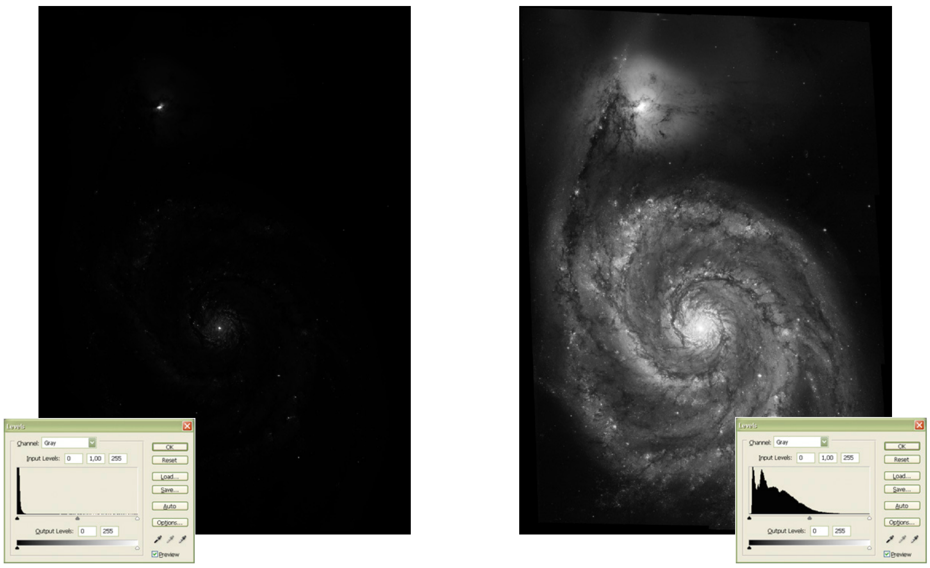

Figure 8. Difference between a linear and a stretched representation of a high dynamic range astronomical observation of Messier 51. Credit: ESO/ESA/NASA Photoshop FITS Liberator/Davide De Martin

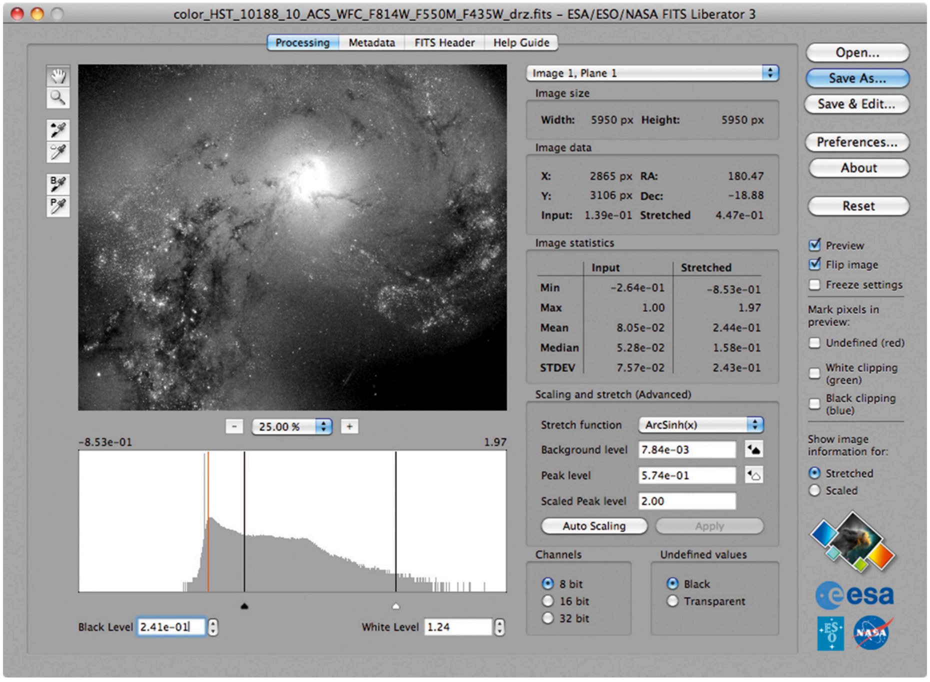

Figure 9. *Adjusting a stretch function. Here, an ArcSinH function is chosen as this often fits well with galaxies with large differences in brightness between the centre and outer parts. Credit: ESO/ESA/NASA Photoshop FITS Liberator*

Furthermore, the choice of filter — narrowband *vs.* broadband — can influence the definition. Observations using narrowband filters are designed to show individual astrophysical processes and most often produce a well-defined and dramatic image.

When adjusting the stretch function (see Figure 9), the aim is to achieve a good balance of midtones: to get a nice contrast without excessively saturating the highlights (the white point) or truncating the darkest parts of the image (Figure 10).

The resulting definition from choosing different stretch functions can be very different, as illustrated in Figure 11.

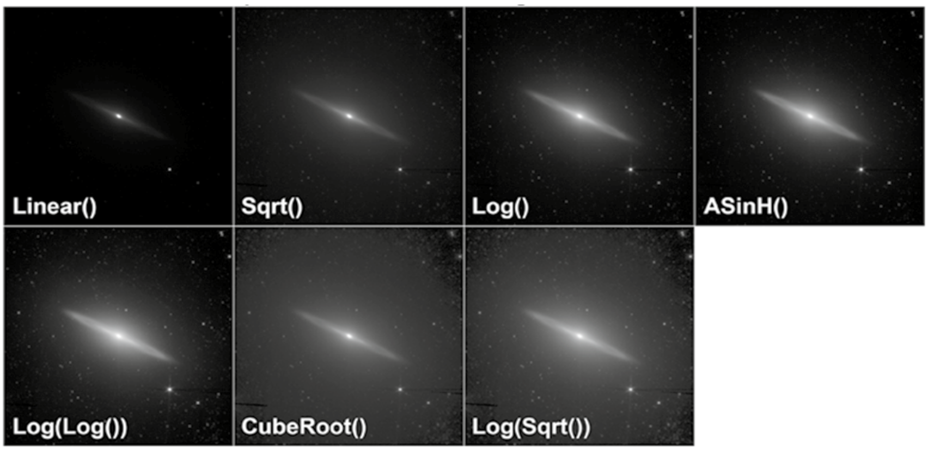

Figure 11. *Different stretch functions give a very different impression of the Sombrero Galaxy as observed with the Spitzer Space Telescope. Credit: Robert Hurt (Spitzer Science Center)*

Figure 10. *Striking the contrast balance. Choosing the right stretch function for a good contrast balance is one of the toughest decisions when processing images. The aim is to achieve a good balance of midtones, and nice white and black points. The right choice here would probably be in the middle, between low contrast (left) and high contrast (right; in the analogue photographic world, contrast is chosen by picking paper of different "hardness"). Credit: Robert Hurt (Spitzer Science Center)*

3. Colour

Images of astronomical objects are usually taken with electronic detectors such as charge-coupled devices (CCDs) or infrared arrays. Similar detectors are found in digital cameras. Telescope images are nearly always greyscale, but are, nevertheless, encoded with colour information that comes either from taking each exposure through a particular filter or from using different detectors, each having different wavelength (colour) sensitivity. Colour outreach images are composited by taking the individual greyscale filter exposures, colourising them and "stacking" them together (see, for example, Figure 12). In principle, three 16-bit greyscale images can create a colour image with 281 474 976 710 656 colours ($65\,565^3$).

In general, the more separated the wavelengths of the chosen filters are, the more colourful and appealing the resulting composite will be. Also, the better the filter set is at sampling the observed wavelength range, the more colourful the result will be. In the visible range, for example, the use of BVR filters ensures a good coverage of the visible spectrum (blue to red), samples a typical (e.g., G dwarf) stellar blackbody well (on both sides of the peak), and produces an image with a wide separation of colours (also known as colour gamut).

The chosen wavelength range will have a characteristic temperature, corresponding to the blackbody peaking in that range. In the visible, this is a few thousand Kelvin; in the thermal infrared, hundreds to tens of Kelvin; and a few to a few tens of Kelvin in the submillimetre. For thermal emission processes, picking a set of filters which cover the peak of the blackbody spectrum, and bracket it, often leads to the best result.

Very interesting optical images result from the combination of at least three continuum bands (e.g., BVR to sample the stellar blackbody and reproduce stars with a good white balance) and at least one additional narrowband image (to sample emission from individual atomic transitions).

Although it is, in principle, possible to assign any colour to any exposure, in our images we rarely deviate from assigning colours in the chromatic order that they have been observed in. In simple terms, for an infrared image, the "reddest" exposure should be red, and the "bluest" blue. In the case of narrowband observations, so-called "enhanced colour images" are seen on rare occasions when the narrowband image stacked on a broadband image is assigned an arbitrary colour.

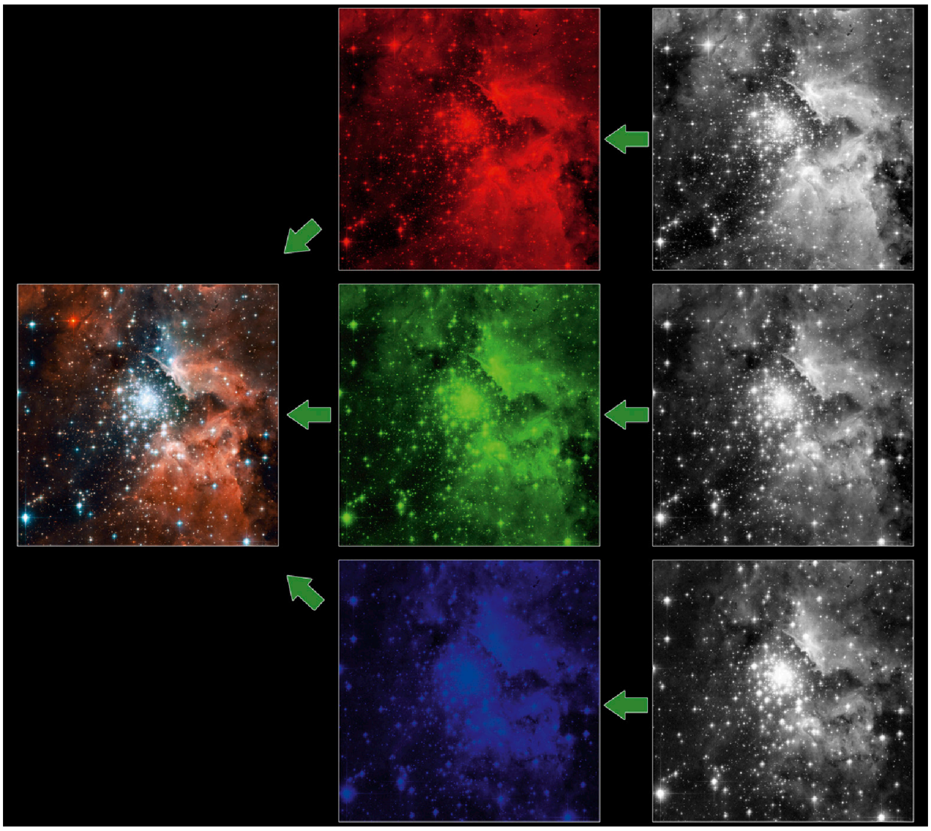

Figure 12. *Colour images are composited by taking individual greyscale filter exposures, colourising them and "stacking" them together as if "sandwiching" film slides together. Credit: The NASA/ESA Hubble Space Telescope/Davide De Martin*

4. Composition

To obtain a pleasing composition and not waste photogenic resolution, the object should in general fill as much of the field of view as possible. The outreach image composition is most often decided in the very last phase when the colour composite is done, just before the image is ready for publication. Since most producers of astronomical images at observatories produce the "raw material" for others to use — journalists, text book writers and movie directors — one can argue that the images should be cropped wider rather than tighter, leaving the final composition to the user's preference. Speaking against this, however, many of these recipients do not have the means to process or even crop large astronomical images efficiently. Moreover, the resolution of images published today needs to be compatible with both large and very small devices. This suggests a need to deliver a final "perfect composition".

Figure 13. *Creative crop (right) of a large image (left). Both crops are aesthetically pleasing and show widely different content, owing to the large photogenic resolution in the image and the resulting richness of detail. Credit: ESO*

On the other hand, the proliferation of very large images today also gives graphic designers the opportunity to be creative, and crop very limited portions of an image for certain applications (Figure 13).

5. Signal-to-noise ratio

To get a good signal-to-noise ratio or "depth" of an image, the exposure time must be sufficient to secure a fairly noise-free representation even in the fainter regions of the object. This usually implies fairly long exposure times, which can be difficult to achieve with large telescopes (see, for example, Figure 14). Sophisticated noise reduction algorithms such as those found in software packages like Photoshop, or in plug-ins like Topaz DeNoise, Noise Ninja or Neat Image, can be applied to mitigate the noise during the last stages of graphical processing.

Figure 14. Short-exposure image with the Very Large Telescope showing a limited signal-to-noise ratio and noise that can distract from the aesthetic viewing pleasure. Credit: ESO

6. Removal of artefacts

Experience shows that one of the things that disturbs the viewing pleasure for members of the public is residual artefacts from the sensor or the telescope. The rule of thumb is simple: while scientists may be able to concentrate only on the parts of the data that are relevant to them, ignoring artefacts, members of the public will focus on anything of non-cosmic. All artefacts must be removed in order to not distract the eye, disturb the aesthetic appeal, or to waste the audience's finite attention span on aspects of the image that are not part of the scientific outreach message. This is something that ESO and ESA/Hubble expend significant manpower on, often to the order of one or two hundred hours of manual cleaning work for a large image. The number of frames must be sufficient to filter cosmic rays and detector blemishes, and to cover inter-chip gaps during astronomical processing.

Conclusion

Turning raw data into aesthetic pictures takes real effort: planning, astronomical

Figure 15. Example of an uncleaned image early in the production (left) and the final clean image (right). Credit: ESO

insight, technical insight, graphical insight and dedication. It is proposed here that at least six main parameters contribute to an astronomical picture's aesthetic appeal: high photogenic resolution, good definition, appealing colour, interesting composition, high signal-to-noise ratio and good removal of artefacts.

In the ideal case, we have a great image when all six parameters are fulfilled — a "Hubble-class image". It is, however, still possible to produce great images with less, but it gets more difficult and compromises have to be made. Some examples of such compromises are:

1. **Photogenic resolution:** If the necessary photogenic resolution is not available (due to atmospheric or weather limitations, a small CCD chip, or use of a small telescope), we can mosaic different exposures together[9]. In some cases, for bright objects, we can also apply so-called lucky imaging, and select just those short exposures where the atmosphere was most stable, and then combine, or stack, the images into an image with super-seeing. Low resolution datasets can also in some cases be combined with higher resolution datasets in different wavebands for a perceived higher resolution.
2. **Definition:** Good definition can be achieved by spending more time tuning the dynamic range compression.
3. **Colour:** If three different exposures through well-separated colour filters are not available, we can create a pseudo-green image by averaging the red and blue exposures, or decide to accept an image that has a smaller range of colours (gamut).
4. **Composition:** Good composition usually comes at the compromise of cropping away parts of a perfectly good image, but it is usually worth it if the aim is to optimise the viewing pleasure of the "innocent" eye that does not know that more data were available.
5. **Signal-to-noise ratio:** For professional telescopes, it is often necessary to use data that comes from rather shallow exposures as the observing time is always in high demand. The compromise can be to accept a noisier image, and then apply advanced noise reduction algorithms. For amateur telescopes, the option is often to spend nights of observing time until the optimal signal-to-noise ratio has been achieved. Impressively deep images can be achieved in this way.
6. **Removal of artefacts:** If a dataset is significantly "dirty", even after the appropriate astronomical processing, it is mostly a simple matter of spending the necessary hours of work on cleaning the image manually. There seems to be no silver bullet, other than endurance.

If you know how to control these six parameters well, know your telescope and data, and are prepared to spend the necessary time on finding your image's niche within this six-parameter space and on finding workarounds and compromises for datasets that are not optimal, we claim that any telescope/imager can deliver aesthetically pleasing astronomical images.

References

Christensen, L. L. 2007, *The hands-on guide for science communicators: a step-by-step approach to public outreach*, 1st edn., (New York: Springer)

Hurt, R. & Christensen, L. L. 2005, *User's Guide, The ESA/ESO/NASA Photoshop FITS Liberator v.3*, http://www.spacetelescope.org/projects/fits_liberator, May 2013

Pierce-Price, D., Hainaut, O. & Christensen, L. L. 2011, *ALMA's potential for visually impressive outreach images*, internal ESO/ALMA outreach report.

Prusinkiewicz & Lindenmayer 1990, *The Algorithmic Beauty of Plants*, 1st edn., (New York: Springer), downloadable as PDF from http://algorithmicbotany.org/papers/abop/abop.pdf

Rector, T. A. et al. 2007, Image-Processing Techniques for the Creation of Presentation-Quality Astronomical Images, The Astronomical Journal, 133, 598 doi:10.1086/510117

Notes

1. High Dynamic Range (HDR), see for instance Wikipedia: http://en.wikipedia.org/wiki/High_dynamic_range_imaging
2. http://www.spacetelescope.org/projects/fits_liberator/
3. http://www.spacetelescope.org/projects/fits_liberator/improc/
4. http://www.spacetelescope.org/projects/fits_liberator/stepbystep/
5. The attentive reader will correctly note that Hubble's main mirror is, strictly speaking, not perfect because of its incorrect polishing, but a correction to near-perfectness is achieved by its instruments.
6. See for example ALMA results at: http://www.eso.org/public/news/archive/search/?adv=&facility=36
7. For comparison, the dynamic range of the human eye without any pupillary adjustment is 1000–10 000. In deep astronomical images the dynamic ranges can reach 10 000. Typical computer screens or printers can only show a dynamic range of 700–1000.
8. See http://en.wikipedia.org/wiki/High_dynamic_range_imaging
9. In a quite extreme case, the VISTA telescope in 2012 delivered a mosaic image of 108 200 × 81 500 pixels with a photogenic resolution of ~ 40 000
10. A 120-hour image of Centaurus A can be seen here: http://goo.gl/WOfyz

Biographies

Lars Lindberg Christensen, President of C55, is a science communication specialist, who is Head of the ESO education and Public Outreach Department (ePOD) in Munich, Germany. He is responsible for public outreach and education for the La Silla-Paranal Observatory, for ESO's part of ALMA and APEX, for the European Extremely Large Telescope, for ESA's part of the Hubble Space Telescope and for the IAU Press Office. Lars has more than 100 publications to his credit, most of them in popular science communication and its theory.

Olivier Hainaut is an astronomer specialising in the study of icy minor bodies in the Solar System, such as comets and trans-neptunian objects. While tracking the faintest and most distant ones, he developed techniques that push the largest telescopes to their limits. For the last few years, Olivier has coordinated ESO's ePOD efforts to produce outreach images using ESO's telescopes.

Douglas Pierce-Price began his career as an astronomer, studying the Galactic Centre, before developing an interest in science communication and outreach. After working as Science Outreach Specialist at the Joint Astronomy Centre in Hawaii he joined ESO in Munich, Germany as Education Officer, before becoming ESO's Public Information Officer for the submillimetre-wavelength telescopes ALMA and APEX, and Deputy Head of the education and Public Outreach Department (ePOD). In 2013, he moved from ePOD to lead the newly created Internal Communication Office at ESO.