FITS: A REMARKABLE ACHIEVEMENT IN INFORMATION EXCHANGE

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Abstract. The FITS format is a remarkable achievement in information handling and sharing. Astronomy is alone among the sciences in having an international data interchange format that is used by virtually all scientists and institutions in the field. The technical and sociological reasons for this success are discussed and a few of the many remarkable scientific results made possible by this information handling are described.

1. Early History

Wells & Greisen (1979) wrote that "With the advent of the WSRT and the VLA in radio astronomy, the increased use of CCD arrays and other digital techniques in optical astronomy, and the development of satellites for astronomical observations at other frequencies, the number of images in digital form has increased enormously." This sentence has become an immense understatement. The need for scientists to carry data between observatories and to their home institutions has kept pace with the progress in astronomical instrumentation. Research projects now normally involve multiple wavelengths and multiple instruments and remote observing has become far more common. In 1979, each institution typically had one or more software packages tailored to its instruments and computing facilities. Almost every institution had developed at least one unique data format, for both internal and external data representation, and a significant body of software based

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on the use of that format. If N institutions wished to exchange data, a total of $N(N-1)$ programs had to be written to perform the translations between these formats. When one of the institutions changed its internal format (and that happened frequently), then the other institutions had to make corresponding changes in their translation programs (if they were able to determine what change was to be made). With the development of a usable interchange format of any sort, this situation is improved dramatically. Each institution needs to write only two programs, those which translate between the internal and the interchange format. And when an institution changes its internal format, it alone is responsible for making corresponding changes in its translation programs. Of course, if the internal format *is* the interchange format, then no translation programs are required.

By 1978, a number of us responsible for major data centers had become tired of writing and rewriting data translation programs and had taken tentative steps toward developing and using a more general format. As early as 1976, Ron Harten (Netherlands Foundation for Radio Astronomy) proposed the use of a transport format. Don Wells (Kitt Peak National Observatory) and Harten subsequently exchanged data in two prototype formats. Following discussions involving representatives of the National Radio Astronomy Observatory (NRAO), KPNO (now National Optical Astronomy Observatory), and the National Science Foundation, W. R. (Bob) Burns of the NRAO wrote a memo in February 1979 urging that active discussions begin on an interchange format. This resulted in a meeting held at the VLA site March 27 and 28, 1979 in which the FITS format was designed by Wells and Greisen with advice from several NRAO staff members at the VLA, particularly Barry Clark. The first magnetic tapes to use the new format were exchanged in April 1979. The first FITS files were written by a PL/I program on an IBM 360 under OS/MFT (32-bit, twos-complement numbers and 8-bit EBCDIC characters) and were read by a Fortran program executing on a CDC 6400 under SCOPE (60-bit, ones-complement numbers and 6-bit "Display Code" characters). This was very near the worst possible combination of environments and yet the interchange worked as intended on the first try. The FITS paper was presented in Trieste by Wells and Greisen in June (1979). In October, Greisen and Harten got together in Holland and developed the "random groups" extension to FITS. That extension involved a more general view of what constituted an image and, with hindsight, should have caused us to change the basic FITS design. It was argued that too much time had already passed and so we chose to make the extension unpleasantly *ad hoc* in order to avoid making obsolete any files already written. This was the first application of the guiding principle "once FITS, always FITS," a principle that has been one of the main reasons for the widespread acceptance of the format. The two papers were submitted to the *Astronomy & Astrophysics Supplement Series*, appearing in June 1981 (Wells *et al.* 1981, Greisen & Harten 1981). By that time, FITS had already become the de facto interchange format for astronomy. Recognizing this fact, the Chairman and Co-Chairman of Commission 5 of the IAU, Bernard Hauck and Gart Westerhout, asked this author to recommend a resolution for Commission 5 at the 1982 meeting in Patras, Greece. It was adopted (IAU, 1982) and a working group to develop further extensions to FITS was established under the leadership of Preben Grosbøl.

2. Basic FITS

The acronym FITS stands for Flexible Image Transport System. This name expresses its main goal — to be a *flexible* means by which *image* data (by now *information* would be a better term) may be *transported* between cooperating computer systems. However, that very flexibility required the development of a quite general way of thinking about data and about the means by which they may correctly be described.

One of the first key decisions in the development of FITS was the selection of the length of the logical record. The choice of 23040 bits (2880 bytes) may seem strange now, but this number is evenly divisible by both the byte and word lengths of all computers that have been sold on the commercial market. It is small enough to be handled by the computers common circa 1979, but large enough to be efficient in writing data to magnetic tape, one record per block. All information for a particular "image" is contained within one file, either on magnetic tape or (now) on disk.

In FITS, character information is represented in 8-bit ASCII form; the other character formats common in 1979 are not allowed. Binary data were initially represented as 8-bit unsigned integers, and 16- and 32-bit twos-complement integers. Since that time, an IEEE-specified floating-point format (specifying the meaning of the bits but not the byte order) has come into wide-spread use in computing, and is now allowed in FITS files. The decision to represent the data in a binary format was initially controversial. However, formatting numbers, which are in binary form within the computer, into ASCII on the transport medium is inaccurate, expensive in computer time, and uses at least three times as many bytes on the output medium. Even in the computers of 2002, formatted reads are surprisingly expensive while the volume of the data has increased enormously. The bytes within the integer and floating numbers are in the order of decreasing significance (so-called "big-endian"). The reverse order ("little-endian"), used internally by many computer architectures including Intel personal computers, is not allowed; the time required for byte swapping is, however, negligible on modern computers.

The information in a FITS file is contained within one or more "header-data units" or HDUs. These consist of one or more logical records giving header information in the form of 80-character ASCII card images, 36 per record. Each card image contains an 8-character keyword (in upper case), usually followed by an equals sign and a value. There are a few required keywords which must occur at the beginning of the first header record. These identify the file as a FITS file and describe the binary format and dimensions of the data portion of the HDU. The required keywords are followed, in any order, by optional keywords, some of which are described in the FITS papers, and are terminated by an END keyword. The last header record is padded with ASCII blanks to its full 2880 characters. FITS writers are allowed to make up any keywords they may require, which allows the format to grow and to adapt to unforeseen developments. Although this is essential to the format's flexibility, it causes a failure to communicate. Until the meaning of a new keyword is described widely, most reading programs will have no idea how to interpret it. However, the header is always human readable and so, with adequate comments and history cards, may often be understood in time.

The data portion of the HDU begins in the first byte of the first logical record following the header record containing the END keyword. The data are a fully packed byte stream broken into logical records with no padding, except that the last data record is padded with zeros to its 2880-byte length. The initial data form described by Wells *et al.* (1981) was an n-dimensional, regularly spaced array. The arrays were described by giving the number of axes and the number of points on each axis in the required keywords. Greisen & Harten (1981) extended this data model to groups of such arrays each preceded by a number of binary "random parameters" describing the array. An example of a random-groups format would be a set of small images surrounding a variety of celestial positions with the random parameters describing the location of those positions. Although the random groups form has been widely used for radio interferometric data, it has largely been replaced by the binary tables form to be described below.

3. Standard FITS extensions

Wells *et al.* (1981) added a great flexibility to the FITS format by specifying that any number of 2880-byte logical records may follow the defined HDU. As might be expected, this led to the development of a variety of extensions, known and accessible only to their inventors. In order to provide a more orderly method for defining conforming extensions to follow the basic HDU, Grosbøl *et al.* (negotiated in 1984, published 1988) defined a small set of new keywords and a general data structure very much like the image and random-groups data structures to be used in future conforming extensions. They stated that "The most important rule for designing new extensions to FITS is that existing FITS tapes must remain valid." The extensions have the same HDU structure as the primary HDU. The header contains required keywords at the beginning to name the type of extension and to describe the binary format and dimensions of the data portion of the HDU. This enables reading programs to determine the type of extension and the number of binary data records that must be read or skipped after parsing only a few keywords. The structure defined by Grosbøl *et al.* (1988) allows for any number of conforming extensions to occur in the data file in any order. The association of the data in the extensions with the data of the primary HDU and each other is indicated by their presence within the single file (Grosbøl *et al.* 1988).

A number of standard extension types were developed in the next few years. The first, by Harten *et al.* (1988), was a companion paper to the general description. It defined a means by which tabular data such as catalogs could be transmitted in a FITS extension in a self-documenting data structure using a fully printable ASCII form. Despite its inefficiency, ASCII tables have been very successful in the exchange of simple catalogs, and provided a way to wrap old representations in a portable framework. The immediate human readability remains an advantage. The second conforming extension type provided for an unlimited number of related, multidimensional images, which might not have the same dimensionality or binary format, to be stored in the same FITS file (Ponz *et al.* 1994). The third, and arguably most important, conforming extension was defined by Cotton *et al.* (1995). This "binary tables convention" was first conceived in about 1984, prototyped at NRAO, and finally negotiated into a more general agreement by 1991. This extension conveys data that are logically organized in a table, an ordered collection of rows and columns. Each row has the same length and each column has the same binary type. However, different columns may be of different binary type including bit arrays, character strings, 8-, 16-, and 32-bit integers, and 32- and 64-bit IEEE floating-point numbers. The big-endian byte order of FITS binary data is retained for all binary table data. Furthermore, a column may be defined to contain an array of numbers of arbitrary size in each row. This extension thereby encompasses all of the previous data forms with the only differences being in the header keywords of the HDU.

Grosbøl *et al.* (1988) also described a change in the FITS standard to allow for data blocking. Up to 10 logical records are allowed to be stored in a single physical record. All physical records within a file must be the same length except the last one which may contain a smaller number of logical records. When the transport medium is a disk file or a transmission over a computer network or the Internet, the meaning of physical record becomes somewhat unclear but does not matter. Nonetheless, the logical record remains 2880 bytes and the only padding of data allowed are the blank fill at the end of the last header record and the zero fill at the end of the last binary data record within each HDU.

Decisions requiring all NASA missions to provide science data products in FITS format led the NASA/Science Office of Standards and Technology (NOST) to establish the FITS Support Office in 1990 to assist NASA missions to understand and implement that format. NOST also commissioned the first of the FITS Technical Panels whose task was to recast the published FITS papers into a form acceptable as an official NASA standard. That process has produced a number of standards in the period from 1990 to 2000. The last (so far), NOST 100-2.0 (Hanisch *et al.* 2001), has been adopted by the IAU FITS Working Group as the official statement of the FITS standard.

Although FITS is a format for data transport, the speed of modern computers allows it to be used as the main internal format in data analysis software packages. The overhead of scanning a full header for a needed parameter rather than having the parameters in a fixed binary structure and the need to swap bytes on some machines is no longer a barrier. To assist in this process, a significant collection of software tools has been developed at NASA Goddard in the high energy astrophysics group and made available to the astronomy community; see, for example, Pence (1992 and 1999). This package (`FITSIO`) together with other FITS-based public-domain packages (referenced from `http://heasarc.gsfc.nasa.gov/docs/software/`) have become mainstays in astronomical research and software development.

4. Successes and failures

FITS has been an unparalleled success. It has enabled countless bytes of data to be transmitted from one computer architecture, observatory, astronomer, and software system to another with every byte being correctly assigned to the proper image or table row and column. It is used by essentially all astronomical observatories, scientists, and software systems either as their fundamental data format or, at least, as an available and understood format. So far as this author knows, there are no other fields of human endeavor which have attained anything like this level of data interchange. Nonetheless, we have achieved only mixed success in exchanging the *meaning* of those bytes we have so accurately transmitted.

Wells (2000) provides a good summary of the many reasons for this success. I will reiterate some of them with perhaps a slightly different view. The basic design negotiations occurred between two, and only two, designers both of whom represented major data producing organizations whose basic role in life is to distribute data to astronomers from other institutions. The two designers were both in a position to implement any agreement in important portions of their employer's software systems. They represented two different fields of astronomy and were able to define a generalization of their prior practices. The encouragement and technical advice provided by the institutions' management and by Barry Clark and the other VLA scientists who participated in some of the meetings were also important.

The initial proposal was appreciated at some level when it first appeared and its adoption was encouraged by a variety of people. Certainly the need for some sort of transport format was clear and basic FITS was able to be read and written in very simplified ways. Harten committed the Westerbork Synthesis Radio Telescope to the format and Rudi Albrecht provided several opportunities for its promotion. Hauk and Westerhout encouraged its adoption by the IAU before it was fully implemented in most places. At the same time, the initial proposal was under-appreciated. On the surface, it was "only" a transport format and it was unlike any that previously existed so that everyone would have to write software to read and write it. In fact, FITS encourages a particular model of data and most software systems designed since 1979 have been profoundly affected by that way of thinking about data. Had this fact been appreciated then, as it is today, I wonder if FITS or any other format could have been so widely adopted. In 1979, a FITS negotiation of very broad impact required only a few days. Now, the negotiation for correcting DATE keywords for our "Y2K" error[1] required approximately two years despite the fact that the basic answer was obvious to everyone. The problem now is that both FITS and systems of time measurement are fundamental *internal* parts of several institution's scientific software systems and any change will obviously have a noticeable *internal* impact.

Advancements in the FITS format have been helped by the creation in May 1991 of a news group called `sci.astro.fits` with a mirrored e-mail exploder called `fitsbits`. Additional e-mail exploders for specialized interests were also created as needed. These exploders have certainly enabled interested parties to remain current with, and contribute to, public on-going discussions of FITS issues. They have also enabled people to ask for, and receive, help with FITS usage and application problems. Discussions on these exploders are capable of becoming quite voluminous and have even achieved some sort of consensus occasionally. Frequently, however, matters are discussed briefly and then apparently dropped.

[1]The original FITS specified DATE strings as 'DD/MM/YY', a form that is unable to define the century. When FITS survived into the next century, a correction was essential. The new strings are in the form 'CCYY-MM-DDThh:mm:ss[.sss...]'.

Several of the fundamental design decisions have also been instrumental in the success of FITS. Probably the most important was the decision that no addition to the format should make existing data sets obsolete. The "once FITS, always FITS" rule has meant that archives of data remain readable by modern FITS software without need for updating and format conversion. FITS reading and writing software may remain static, so long as the needs of that software remain static. In 1979, software was "free" and computers were expensive. Now, super computers are essentially free, but good software has become extremely expensive. If the format remains stable, software costs are minimized. Furthermore, if the format were to undergo a major revision, many institutions might take that opportunity to select an alternative format.

The decisions to allow new keywords and "special records" following the defined ones were also major sources of flexibility and longevity for the FITS format. The generalized extensions agreement (Grosbøl *et al.* 1988) provided a framework within which complex agreements over data structures could be negotiated, but it carefully did not rule out new types of special records to follow the standard extensions.

FITS is a syntactic standard, not a semantic standard. It has been very successful therefore in conveying the form or structure of the data, but it has had notably less success in conveying the meaning of the data. Generalized FITS reading programs can read almost any FITS binary table and can convert, with limitations, the bytes into the internal format of the host software system. The software may then use generalized routines to display for the user the names and data contents of the table columns. However, without additional negotiated conventions, that software cannot know that, for example, column 4 contains calibration data to be applied to the image in column 7 whose coordinates are given in columns 5 and 6.

Wells *et al.* (1981) suggested a variety of keywords for defining coordinates and mandated the use of International System of Units (*e.g.,* meters, kilograms, seconds) for units. Despite the IAU endorsement, these suggestions were widely ignored in favor of "more natural" units and locally invented keywords which duplicate the meaning of existing keywords.

Another impediment to data interchange arose from the very flexibility of FITS. It is more difficult, time consuming, and expensive to write software to handle a wide range of possible input data even when the analysis algorithms might be capable of performing interesting operations on that range of data. Therefore, organizations often choose to write programs for a limited subset of the FITS capabilities. A great many programs have been written, for example, to read only two-dimensional images since that is all that the software designers considered that they would need to analyze. These programs were not written to accommodate the more general data representations given in Wells *et al.* (1981) in which "degenerate" (1-pixel) axes may be used to convey additional coordinate information. Thus, incompatibility arises between software systems that are aware, or not, of such representations and interoperability is compromised. Since software is expensive, and updating legacy applications is prone to unearthing or causing other problems, advances in the FITS standard must attempt to accommodate the varying levels of generality. This makes negotiations much more difficult, often resulting in compromises that are less than ideal.

There are criticisms of FITS that should be mentioned here, although many of these suggestions would tend, in my opinion, to diminish the simplicity and predictability which have been among the reasons for FITS' acceptance. (In fact, the strongest complaint heard circa 1980 was that binary data were too hard to read and that we should have provided a character form for the primary image data.) Some suggestions would even cause uncorrected FITS readers to misinterpret the headers, rather than simply failing to understand new constructs and keywords. This must be avoided in order to retain the "once FITS, always FITS" rule.

Although the logical association of FITS HDUs is explicitly conveyed by their presence within a single file, no additional information about that association is defined. Advanced software systems frequently make good use of hierarchal data structures, but they have no way to represent those structures in standard FITS. A set of the coordinates of an image may be viewed as an "object" in modern software parlance. Several such objects may, within the proposals discussed below, be used to describe the same image. But no "inheritance" from one object to another has been defined even within the same HDU, let alone between HDUs. The limitation of FITS keywords to eight, upper-case characters frequently frustrates designers of new concepts. However, the discipline that rule enforces has caused concepts to be more carefully considered and then limited them to manageable dimensions. The requirement to specify the length of the data in advance (in the header) poses significant complications for data acquisition systems.

5. World Coordinate Systems

World coordinates are the coordinates that serve to locate a measurement in some multi-dimensional parameter space. They include, for example, a measurable quantity such as the frequency or wavelength associated with each point in a spectrum or the longitude and latitude in a spherical coordinate system which define a direction in space. World coordinates may also include enumerations, such as "Stokes parameters", which do not form a normal image axis since interpolation along such axes is not meaningful.

Wells *et al.* (1981) recognized the need for world coordinate system

(WCS) keywords and provided keywords for each axis of the image to specify coordinate type and a reference point for which the pixel coordinate, a coordinate value, and an increment were given. An undefined "rotation" parameter was also provided for each axis. These descriptions were kept simple so that controversy over coordinate specification would not interfere with adoption of the basic structures of the format. While participating in the development of the AIPS software package of the NRAO—see the chapter on AIPS in this volume—Greisen (1983, 1986) found it necessary to supply additional details to the coordinate definitions for spectral and celestial coordinates. These specifications were widely used in radio astronomy and some X-ray, optical, and infra-red projects also adopted them.

The negotiations on WCS have been the most protracted and complex negotiations in the history of FITS. They began with a NASA-sponsored conference held in January 1988 at the NRAO in Charlottesville. That conference recommended that a general WCS standard be based on the AIPS specifications where possible and extended to support a more general approach to handling scaling and skew (Hanisch & Wells 1988). Several variations on the notations suggested in that meeting made their way into software developments at the Space Telescope Science Institute (STScI) for data from the Hubble Space Telescope and other NASA missions and at the National Optical Astronomy Observatory (NOAO) in the IRAF software package. In response to a discussion held at the 1992 ADASS meeting, Greisen and Mark Calabretta (Australia Telescope National Facility) prepared a draft standard by December 1992 and presented it at the June 1993 AAS meeting in Berkeley (1993). Discussions with Doug Tody (NOAO) at that time led to a new version of the proposal, distributed by August 1993, which changed some of the notations of 1988 (Greisen & Calabretta 1995). A new version was offered in 1996 that added WCS keywords for binary table extensions and a method for converting real images (*e.g.,* with warps) into the ideal projective geometries previously described.

Why, after some eight years, had the community not reached an agreement? Previous negotiations had involved individuals from different areas of astronomy with the clout to implement their proposals. By 1995, Calabretta had written `wcslib`, a portable subroutine package implementing the proposal which was (and is) widely used. Despite this, there was a perception that the proposal solved the WCS problems of radio astronomy, but not of other kinds of instruments. Groups that should have invested effort to correct this situation did not. Project managers were satisfied if their software could understand its own WCS and saw little need for the expense of creating and implementing higher levels of standardization. Many of these projects were able, with some pain, to work around the lack of standards when reading a foreign WCS. Furthermore, there was, and still is, little personal reward or recognition for major efforts toward standardization and such efforts must be undertaken above and beyond other responsibilities.

These issues continued to hinder the WCS negotiations. WCS was discussed at some length at the ADASS meetings of 1997 and 1998 with the results presented in 1999 by Calabretta & Greisen (2000). The participants at the 1999 meeting voted that the papers should now be presented to the regional FITS Committees for a vote. But that did not happen. Finally on 30 June 2001, a significant generalization of the three papers (the paper had been split and spectral axes had been added) was suggested by Francisco Valdes, Doug Tody, and Lindsey Davis of NOAO. Their proposal resulted in a separation of instrumental peculiarities into a Paper IV while Papers I–III would be concerned with ideal coordinates. That proposal was presented at the 2001 ADASS and additional compromises were reached. But there were serious differences of opinion remaining which were only resolved with the skillful mediations of Bob Hanisch (STScI) and by simply recognizing the validity of both of the competing nomenclatures.

The WCS negotiations have been exhausting. Several groups helped in areas of their expertise, particularly tables and representations of units, and a very few individuals were consistently helpful and supportive. However, the lengthy periods of inactivity, the apparent inattention of knowledgeable individuals, the perceived antagonism, and lengthy arguments over issues that may be considered matters of taste make undertaking a new FITS proposal quite daunting. And that neglects the very real difficulties associated with a complex subject like world coordinates. The long period used by this negotiation also allowed WCS solutions that differed from the early proposals to appear in a great many FITS files, thereby achieving a need to be supported without having any community agreement.

All this being said and despite a few committee-like compromises, the resulting papers are far more comprehensive, accurate, and readable than the drafts of even one or two years ago. Although the main portions resemble the earliest drafts, significant details have been added, strengthened, and corrected in order to insure functional implementation. The first two WCS papers have now passed the North American FITS Committee and have been submitted (Greisen & Calabretta 2002 and Calabretta & Greisen 2002). Paper III on spectral coordinates is in a nearly final draft form (Greisen *et al.* 2003). Paper IV on distortion correction is in preparation.

The WCS experience need not be repeated. In the new Virtual Observatory framework, international agreement was reached on a representation of tabular data in XML (drawing upon the vast body of FITS experience) in a matter of months (Ochsenbein *et al.* 2002). The process can work well — and quickly — when there is a will to succeed. Our community needs to adopt a more aggressive and inclusive process for standards development.

6. Scientific achievements of FITS

This section is comparable to a section on the intellectual achievements of a spoken language[2] or even a screwdriver. Like them, FITS is a basic tool that makes all sorts of things possible and like them, their use is never mentioned. Because FITS is nearly ubiquitous, a user of one telescope may choose to reduce the data not with the software provided for that telescope, but with software provided in connection with some other, usually similar, telescope. FITS allows convenience, familiarity, and availability of algorithms to determine where and how a scientist analyzes the data. Furthermore, it determines when the analysis may take place. If data are archived in FITS, the very stability of the format guarantees that the data are accessible to the scientist with a new scientific question, perspective, or algorithm long into the future. FITS is also widely used to serve images over the web (*e.g.,* Condon *et al.* 1998) and will be a major tool employed by the Virtual Observatory (*e.g.,* Szalay 2001).

FITS enables the scientist to observe with different instruments over a wide range of wavelengths such as X-ray, optical, infra-red, and radio and then to bring all the images together in order to learn much more about the physics of the objects. Multi-wavelength projects now seem routine or even obligatory, whereas they were rarely carried out when FITS was first invented. So that the images may be aligned, an accurate WCS must be available for each image. Until recently, such information was not always available in widely understood keywords on all FITS files. That situation is improving.

One early experiment, conducted around the time FITS was first accepted by the IAU, is illustrated in Fig. 1. The twin, wide-angle-tail radio galaxy 3C75 was observed in 1983 by Owen *et al.* (1985) using the Very Large Array at 20- and 6-cm wavelength in multiple configurations. Those data were calibrated and imaged with the NRAO software of that era and written as FITS images. Also in 1983, CCD images were made at R and B bands using the NOAO 0.9-m telescope and written on FITS tapes. The images were then processed in the same software system to compare the appearance of the galaxy at these four frequencies. The optical data had to have the WCS parameters determined by traditional means since they were not recorded on the FITS tape (and probably were unavailable at the time the tape was written). The WCS parameters of the radio image are well known due to the nature of the instrument. The two central dots, seen in both radio and optical, are the twin nuclei of the central galaxy in

[2]FITS does well in defining the syntax (grammar) but not so well on the semantics (vocabulary). Non-standard keywords are comparable to different dialects, while new standard keywords are like new words which have to be learned.

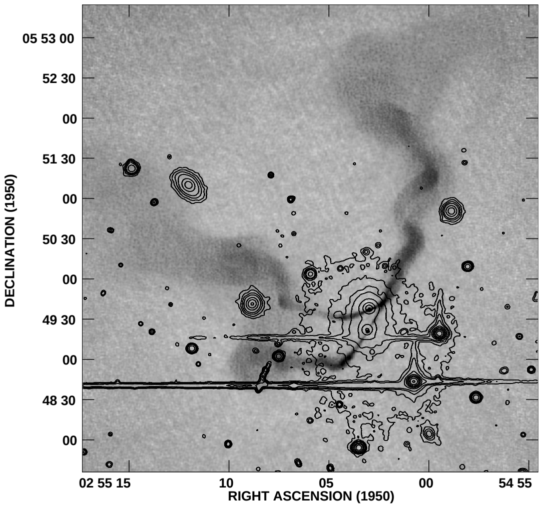

Figure 1. 3C75 observed in B band (contours) at the NOAO 0.9-m telescope by Frazer N. Owen and Richard A. White in 1983. The gray-scale image was also made in 1983 using the NRAO VLA at 6-cm wavelength by Owen *et al.* (1985).

the cluster of galaxies Abell 400. The radio jets are bent, possibly by the motion of the nuclei through the hot gas in the cluster. On the right side of the image, the jets appear to interact and possibly are wrapped around each other. The diffuse stellar light of the galaxy may be seen surrounding the two nuclei. The two objects with spikes are stars; several other galaxies and foreground stars may also be seen in the contours.

There are so many examples of this multi-wavelength astrophysics that any selection done here should be regarded as random and certainly neglects the most important such papers. Nonetheless, there are several items worth mentioning. The web site of the NRAO is beginning to contain a gallery of images at `http://www.nrao.edu/imagegallery`. A number of the images contain optical as well as radio data, particularly the pages on radio galaxies and neutral hydrogen in galaxies. See also Hibbard *et al.* for the latter. Bauer *al.* (2000) have correlated ROSAT and NRAO VLA Sky Survey source lists and then identified a large number of objects with them optically. Falcke *et al.* (1998) have found striking high-resolution correlations between the Hα and radio structures in Seyfert galaxies using Hubble Space Telescope and VLA imagery. Blanton *et al.* (2001) use Chandra X-ray and VLA radio images of a cooling-flow cluster of galaxies to show a coincidence in the X-ray and radio central core sources and a correlation between the radio lobes and holes in the X-ray emission. They write "The data are consistent with the radio source displacing and compressing, and

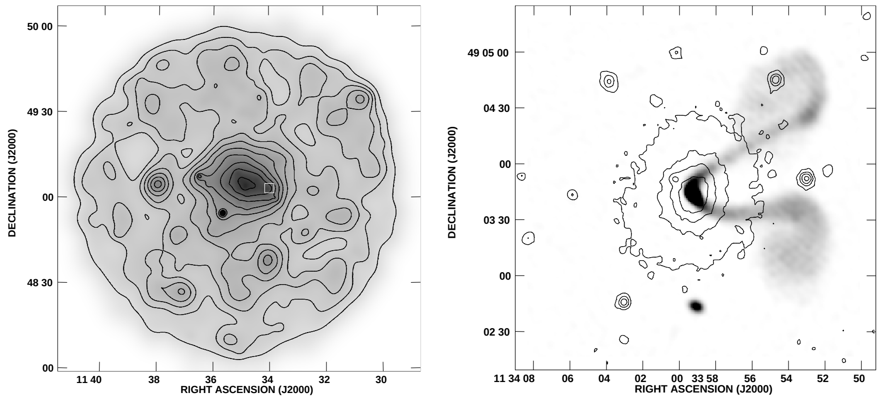

Figure 2. Left: galaxy cluster Abell 1314 observed in X-rays with ROSAT; the small white box shows the location of the field containing IC 708. Right: the radio galaxy IC 708 observed at 4.5 GHz with the VLA in gray-scale with contours of the optical image from the POSS.

at the same time being confined by, the X-ray gas." Chu *et al.* (2001) have combined Chandra X-ray and Hubble Space Telescope Hα imagery to analyze the densities and temperatures in NGC 6543, the Cat's Eye Nebula.

Aball 1314, a cluster of galaxies located at a redshift of 0.0338, provides another example. It contains large diameter intra-cluster X-ray emission seen in the ROSAT image[3] in the left half of Fig. 2. The cluster contains IC 711, a radio galaxy with an exceptionally long tail extending over 600 kpc in projection, and the radio galaxy IC 708, illustrated in the right half of Fig. 2. The gray-scale image is of the radio source at 4.535 GHz made with the Very Large Array at a resolution of about 5 arc seconds (Clarke & Vogt 2002). The optical image shown in contours is taken from the POSS[4] and shows a diffuse galaxy coincident with the central radio source. The unusual radio structure of IC 708 may be related to its gravitational interaction with the nearby galaxy IC 709 and the cluster center. In this scenario, our line of sight lies close to the orbital plane of the radio source. The compact radio source south of IC 708 has no obvious counterpart on the optical image and is likely to be an unrelated background source.

[3]This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center.

[4]Based on photographic data of the National Geographic Society – Palomar Observatory Sky Survey (NGS-POSS) obtained using the Oschin Telescope on Palomar Mountain. The NGS-POSS was funded by a grant from the National Geographic Society to the California Institute of Technology. The plates were processed into the present compressed digital form with their permission. The Digitized Sky Survey was produced at the Space Telescope Science Institute under US Government grant NAG W-2166.

7. Summary

FITS, the Flexible Image Transport System, provides methods by which astronomers can exchange their data. It is efficient, straightforward, unambiguous, interpretable, flexible, and powerful. It achieves these (1) by using binary recording of the image and tabular data at user-selected accuracy, (2) by specifying fixed logical record lengths, industry-standard coding of characters and binary data, and a simple general structure, (3) by requiring a minimal and accurate description of the data records, (4) by expressing all header parameters in ASCII text which can be read by humans as well as computers, (5) by providing a general set of keywords, (6) by making a general form for extensions and defining the extremely general binary tables extension, and (7) by allowing the creation of new keywords in the header and new record types following the main HDU. FITS is used throughout the astronomical community and has been adopted as an IAU standard.

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