Experimental Astronomy (2019) 47:359–380
https://doi.org/10.1007/s10686-019-09633-z

REVIEW ARTICLE

Astronomical data fusion: recent progress and future prospects — a survey

Ce Yu[1] · Bingyao Li[1] · Jian Xiao[1] · Chao Sun[1] · Shanjiang Tang[1] · Chongke Bi[1] · Chenzhou Cui[2] · Dongwei Fan[2]

Received: 4 December 2018 / Accepted: 12 June 2019 / Published online: 25 June 2019

Abstract
Over the past year, the discovery of the first electromagnetic counterparts to sources of gravitational waves and high-energy neutrinos has brought us to the new era of ”multi-messenger” astrophysics (MMA). These new events provide deep insights into astrophysics, meanwhile, lead to the development of astronomical data fusion techniques. Each messenger carries information from different observation process and fusing all messengers can therefore provide the best understanding of the celestial objects’ attributes and expose various astrophysical phenomena. Over the decades, for the full exploitation of multi-band astronomical data, advanced unified platforms and data fusion techniques have been developed and become a research topic of interest for the astronomical community. In this paper, we present a systematic review of the popular and state-of-the-art fusion methods and platforms in different formats of astronomical data, aiming to give a comprehensive introduction to the current progress in this field; at the same time, we put forward insightful prospects for future study of multi-messenger data fusion, hoping to provide new thoughts for researchers in MMA era.

Keywords Astronomical data fusion · Multi-messenger astrophysics · Virtual observatory · Cross-matching · Astronomical image fusion · Image mosaic

1 Introduction

For a long time, astronomers and physicists have routinely carried out observations of cosmic sources by electromagnetic means, and realized the era of full wavelength

✉ Ce Yu
yuce@tju.edu.cn

1 College of Intelligence and Computing, Tianjin University, Tianjin 300350, China

2 National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China

astronomy. Within the past year, the discovery of the first electromagnetic counterparts to a gravitational wave transient GW170817 [1], and identification and characterization of the gamma-ray blazar TXS 0506+056 coincident with the IceCube-170922A high-energy neutrino [39], have brought us to a new moment—the era of multi-messenger astrophysics (MMA). MMA is a globally coordinated observations of cosmic rays, neutrinos, gravitational waves, and electromagnetic radiation across a broad range of wavelengths [39]. Just as the breakthrough of the above astronomical events, the combination of different messengers is expected to yield crucial information on the mechanisms energizing the most powerful astrophysical sources.

The new dawn of MMA provides the unique opportunities for various astronomical events, while bringing with new challenges. As shown in Table 1, a wide range of astronomical observation equipment, spanning the electromagnetic spectrum and gravitational-wave, will supply an exponential growth of data volume greater than astronomy previously knew. Unfortunately, each apparatus can only observe data in a limited band. To full exploitation of the MMA's opportunity, it is clear that astronomical data fusion technology—aiming to generate a composite dataset from multiple observation datasets containing complementary data of the same celestial object or area—will be urgently required to rapidly analyze the multi-messenger datasets that are from electromagnetic waves to gravitational-waves to high-energy neutrinos.

Several surveys focused on the topic of data analysis have contributed to the field of astronomy, such as source detection approaches (e.g. [62]), astronomical image processing (e.g. [87]), etc. However, a review on astronomical data fusion is missed. In this paper, we provide a first-of-its-kind survey on astronomical data fusion technology, aiming to give a comprehensive introduction to the current progress in

Table 1 Notable astronomical facilities in different wavebands

Waveband	Name (Year)
Radio	SKA (planned), FAST (2016), ASKAP (2014), LOFAR (2013), LMT (2011), Green Bank (2000), VLA (1980), Nancay (1965)
Infrared	Herschel (2009), WISE (2009), Hubble WFC3 (2009), VISTA (2008), Spitzer (2003), UKIRT (1978)
Optical	E-ELT (planned), LSST (2018), LAMOST (2008), GTC (2007), GEMINI (2001), SUBQRU (2000), VLT (1998), Keck I/ Keck II (1993/1996)
Ultraviolet	LUT (2013), Hisaki (2013), GALEX (2003), FUSE (1996)
X-rays	ATHENA (planned), Arcus (planned), eXTP (planned), eROSITA (2019), HXMT (2017), Hitomi (2016), Astrosat (2015), XMM-Newton (1999), Chandra(AXAF) (1999)
Gamma rays	CTA (planned), HAWC (2015), HESS (2012), GLAST (2008), AGILE (2007), VERITAS (2007), Swift (2004), MAGIC (2004), INTEGRAL (2002)
Gravitational-wave	KAGRA (2018), Advanced Virgo (2016), Advanced LIGO (2015), CLIO (2006)
Neutrino	KM3NeT (planned), GRAND (planned), IceCube (2010), ANTARES (2006), AMANDA (2000), Super-K (1987)

astronomical data fusion and to indicate the directions for future research in MMA era.

The astronomical data fusion is a broad subject and data acquired in different formats or wavebands present different features and behaviors. Thus, in order to accommodate the variety of the requirements, the work area of astronomical data fusion has covered a range of domains, such as catalog cross-matching, multi-band image fusion, image mosaic of the same band, etc. The rest of the paper will cover them in detail. Section 2 focuses on the astronomical catalog cross-matching. A detailed review of multi-band astronomical image fusion and single source image mosaic are presented in Sections 3 and 4, respectively. Section 5 introduces the virtual observatories and their development. The last section draws a conclusion from our work and provides prospects for future work of multi-messenger fusion.

2 Multi-band astronomical catalog cross matching

Astronomical catalogs include standard quantitative data generated after calibration and photometry on the observation data. They generally include coordinates, star brightness, temperature and other information in tabular form, each row referring to a celestial object and each column being an attribute of the object. Astronomical catalog is the most commonly used format in astronomical researches, thus, lots of groups have devoted efforts to the optimization methods and easy-to-use platforms of astronomical catalog fusion.

2.1 Cross-matching technology

Cross-matching is a key technology in astronomical catalog fusion, which refers to performing one-to-one matches among heterogeneous catalogs based on the approximate coincidence of the source coordinates. Due to the differences in observation instruments and calibration methods, the same celestial object might have slightly different coordinates on different catalogs. Therefore, a distance threshold based on the calibration errors and other considerations is the condition for identifying whether two celestial objects are the same one. Generally, the angular distance between two objects *dist* and the distance threshold *gamma* are defined as:

$$dist = \arccos(\sin(dec_1)\sin(dec_2) + \cos(dec_1)\cos(dec_2)\cos(|ra_1 - ra_2|)) \quad (1)$$

$$gamma = 3 * \sqrt{r_1^2 + r_2^2} \quad (2)$$

Here, (ra_1, dec_1) and (ra_2, dec_2) represent the coordinates of two celestial object O_1 and O_2, r_1 and r_2 are the error radius of two astronomical catalogs. The cross-matching problem is to find all pairs (O_1, O_2) where $dist(O_1, O_2) \leqslant gamma$.

2.2 Optimization methods

In principle, at the base of any kind of catalog cross-matching, each source of a first catalog should be compared with all counterparts contained in a second catalog [72]. This procedure, if performed in the exhaustive pairwise-based way, is extremely time consuming, due to the large amount of objects. Therefore, various optimization solutions to this problem have been proposed. Table 2 shows the summary of the major astronomical catalog cross-matching methods and the adopted strategies.

2.2.1 Index-based methods

In the past few decades, several sky partitioning index-based methods have been proposed to speed up cross-matching. Zones [32], the Hierarchical Triangular Mesh (HTM) [51], the Hierarchical Equal Area isoLatitude Pixelisation (HEALPix) [30], and Quad Tree Cube (Q3C) [49] are four main-stream sky indexing methods for celestial objects. The common idea of them is that, the whole sky is partitioned into a fixed number of regions, and each celestial object in the same region are assigned to the same index or indices. Therefore, only adjacent regions will be used to perform cross-matching, which greatly reduces the computational complexity.

Zones, an early cross-matching method proposed by [32], partitioned the spherical space into zones, each of which are the declination tripes of equal height. This algorithm was implemented on a single Microsoft SQL server. Nietosantisteban et al. [65, 66] parallelized the Zones algorithm on multiple SQL servers, and cross-matching of SDSS DR3 and 2MASS with eight servers in 20 min. Wang et al. [82] developed a zoneMatch algorithm, which sorts the points in each zone by their *ra* values and performs binary search in each zone. They adapted the zones index to a single GPU, and completed cross-matching of million-scale catalogs in a few seconds. Budavari and Lee [16, 17] designed a Xmatch tool and deployed it into a multiple GPU environment, which cross-matched two catalogs with 450 million sources and 15 million sources in 4 min. Additionally, Zone-based optimization algorithms have been proposed in the last decade. Optimized Zones (OptZones) algorithm proposed by [6] is an improved form of the Zones algorithm that exploits the LSST-specific assumption that each zone's neighbor set contains a maximum of three zones. The main advantage is that the neighbor set of a zone can be easily computed on the fly, and zone neighbor information need not be precomputed and explicitly maintained like in Zones. Two algorithms performance are evaluated in [50] with hybrid SQL server. The experimental evaluation provides insights about how architectural characteristics of the systems affect the performance of the spatial cross-matching algorithms. Ma et al. [57] proposed Euclidean-Zone, which used the euclidean distance for faster neighbor point queries, and they also provided an OpenMP parallelized version. Fan et al. [24] modified the original zones algorithm by firstly filtering out irrelevant objects with sky coverage information. Li et al. [55] expressed cross-matching problem as a join query statement, and combined zones algorithm with bucket-based Map-side join algorithm.

The HTM index proposed by [51] subdivides the spherical surface into triangles of nearly equal shape and size. Its division starts with eight triangles, four on the Northern and four on the Southern hemisphere, each one partitioned into four smaller triangles at the next level. Thus, the HTM index is particularly good at supporting searches at different resolutions, from arc seconds to hemispheres. Mi et al. [63]

Table 2 Major optimized methods for astronomical catalog cross-matching

Methods		Ref.	Notes	Evaluation environment
Index-based	Zones	Gray et al. [31, 32]	First proposed Zones algorithm	Microsoft SQL server
		Nietosantisteban et al. [65, 66]	Parallelized the zones-based algorithm	Eight SQL servers
		Becla et al. [6]	Optimized the zones algorithm method	Hybrid MySQL cluster
		Wang et al. [82]	Proposed a zones-based GPU algorithm	One single GPU
		Budavari and Lee [16, 17]	Designed a GPU-based cross-matching tool	Six GPUs on a single node
		Fan et al. [24]	Proposed a dropout detection method	One single server
	HTM	Kunszt et al. [51]	First proposed HTM index method	Microsoft SQL server
		Mi et al. [63]	A Cross-Matching program based on the directed join algorithm in MapReduce	A cluster of five nodes
		Soumagnac and Ofek [74]	Reformatted catalog into HDF5 files format	N/A
	HEALPix	Gorski et al. [30]	First proposed HEALPix index method	N/A
		Zhao et al. [85]	Considered the block-edge problem	One single MySQL server
		Pineau et al. [70]	Processed the HEALPix-based cross-matching in parallel	One server with two hyperthread quad-core CPUs
		Peng et al. [68]	Combined HTM and HEALPix to solve the block-edge problem	One server, multiple threads
		Jia et al. [46]	Combined an indexed-loop join approach for cross-matching	A CPU-GPU cluster of seven nodes
		Jia and Luo [45]	Adopted a MASJ method for cross-matching	A CPU-GPU cluster of six nodes
	Q3C	Koposov and Bartunov [49]	First proposed Q3C index method	N/A
		Han et al. [37]	Provided a cross-matching tool based on PostgreSQL and Q3C	One single server
Bayesian statistics		Budavári and Szalay [18]	The foundation of the unified framework in Bayesian approach	N/A
		Fan et al. [25]	Extended the Bayesian approach to include an explicit geometric model	N/A
		Pineau et al. [71]	Proposed a statistical framework for multi-catalog cross-identification	N/A

used the HTM index to partition the catalog into hierarchical triangular meshes, and designed a cross-matching program based on the directed join algorithm in MapReduce. In [74], the catalogs were also partitioned into hierarchical triangular meshes using HTM index method and stored in HDF5 files. This cross-matching method supports dozens of astronomical catalogs.

HEALPix [30] is a genuinely curvilinear partition of the sphere into exactly equal area quadrilaterals of varying shape. The partition strategy of HEALPix is the same as HTM. The difference between the two spatial-indexing functions is that HEALPix partitioning is based on quadrilaterals, starting with twelve quadrilaterals. Pineau et al. [70] employed HEALPix as the partitioning scheme and finished the cross-matching of 2MASS (470 million objects) with USNOB1 (1 billion objects) on a machine with two hyper-threaded quad-core CPUs in 30 min. Zhao et al. [85] designed a parallel cross-matching function using HEALPix on a single SQL server and cross-matched two catalogs with 470 million sources and 100 million sources in 32 min. The block-edge problem, which refers to objects in different catalogs correspond to the same object but falling in different pieces of the sky partition, is also considered in their work. The solution is to expand a HEALPix block with an opportunely dimensioned border. In [68], they combined HEALPix and HTM indexing function shapes to reduce the block-edge problem, and submitted the analysis to a pool of threads to speed up cross-matching. With the increasing scale of catalogs, the HEALPix index also implemented in GPU environment. Jia et al. [46] took an indexed-loop join approach utilizing the HEALPix index and cross-matched billion-record catalogs on a seven-node CPU-GPU cluster under 10 minutes. However, such method usually leads to a problem where the sample set is sent in the cluster multiple times. To overcome these issues, Jia and Luo [45] improved previous work by adopting a Multi-Assignment Single Join (MASJ) method and performed cross-matching on a six-node CPU-GPU cluster, which achieved a speedup of 2.69 times over a previous algorithm.

The strategy of Q3C [49] is similar to other sky-indexing schemes, but partitioned into the cube. Each face of the cube is a quad tree structure. The computations of Q3C are much simpler than in HTM and HEALPix due to the usage of the quad tree in the square. The special look-up tables that can speed up the computations are utilized, which make it faster than HTM in the case of high depth of segmentation. The Q3C is mainly used in PostgreSQL database. Landais et al. [53] were largely inspired from Q3C and built a 2D PostgreSQL library HEALPiX-Tree-C (H3C). It has the same functionalities and implementation environment with Q3C, but works with the HEALPix algorithm. More recently, Han et al. [37] developed a cross-matching tool that is based on the PostgreSQL database and uses Q3C as the core index, facilitating the cross-matching work of massive astronomical data.

2.2.2 Bayesian statistics methods

The main criterion of the above cross-matching methods is the approximate coincidence of celestial coordinates (positional cross-matching). There are also other kinds of approach, which make use of the positional mechanism supplemented by statistical analysis used to select the best candidates, like the Bayesian statistics. Budavári and Szalay [18] proposed a unified framework based on Bayesian model for cross-matching astronomical point sources, and taking physical properties, such as colors, redshift, and luminosity, into account. Most recently, Fan et al. [25] extended this model to include an explicit geometric model for cross-matching radio catalogs, which contains physical properties of celestial objects other than the point coordinates. Pineau et al. [71] developed a Bayesian statistical framework for multi-catalog cross-correlation and cross-identification based on explicit simplified catalog models. Salvato et al. [73] proposed Nway—a new Bayesian statistics based algorithm—to provide reliable counterpart associations for the first time.

2.3 Web-based services

Several virtual observatories have developed their own software packages or toolkits for publishing and analyzing data. Among these web-based services or stand-alone tool, there are also special features that offer cross-matching function. We have summarized the services that widely used by astronomers in Table 3.

VizieR[1] [67], an astronomical catalogs database operated at the *Centre de Données astronomiques de Strasbourg* (CDS), provides access to the most complete library of published astronomical catalogs and data tables available on line organized in a self-documented database. Query tool allows the user to select relevant data tables and to extract and format records matching given criteria. It also offers the function of cross-identification of small datasets and self-uploaded dataset and existing datasets cross-matching.

SIMBAD[2] [83], is the reference database contains identifications, ”basic data”, bibliographical references, and selected observational measurements for more than 2.7 million astronomical objects outside the solar system. It also developed and maintained by CDS. SIMBAD has various query modes, such as object name, coordinates, and other criteria. Similar to VizieR, the records number of cross-matching cannot be too large.

Open SkyQuery[3] [33], one of the prototypes for managing multiple astronomical archives, offers distributed queries and cross-matching service over a collection of astronomy databases. The portal can query large, physically distributed databases of astronomical objects such as the Sloan Digital Sky Survey, 2MASS catalog, ROSAT All-Sky Survey, and the FIRST and NVSS radio surveys, mine their metadata, and perform inter-catalog operations such as cross-matching.

The Starlink Tables Infrastructure Library Tool Set (STILTS)[4] [80], is a package of command-line tools for performing versatile and powerful manipulations on astronomical catalogs. It supports various cross-matching criteria, including a global or per-row maximum angular separation, proximity in two- or three-dimensional Cartesian space, or requiring proximity in flux value.

[1] http://vizier.u-strasbg.fr/
[2] http://simbad.u-strasbg.fr/simbad/
[3] http://www.OpenSky-Query.net/
[4] http://www.starlink.ac.uk/stilts/

Table 3 Commonly used astronomical catalog cross-matching services

Name	Ref.	Notes
VizieR	Ochsenbein et al. [67]	Observation data query, cross-identification of small datasets
SIMBAD	Wenger et al. [83]	Basic data, cross-identifications, bibliography and measurements for astronomical objects outside the solar system
SkyQuery	Malik et al. [60]	A distributed query and cross-matching service for the VO community
STILTS	Taylor [80]	A set of command-line tools based on the STIL libraries to process tabular data
TOPCAT	Taylor [79]	An interactive graphical viewer and editor for tabular data
CDS-Xmatch	Boch et al. [15]	A data fusion and management tool; cross-identify sources between very large catalogs or user-uploaded datasets
ARCHES	Motch et al. [64]	An astronomical resource cross-matching tool for High Energy studies based on Bayesian probabilities

The Tool for OPerations on Catalogues And Tables (TOPCAT)[5] [79], an interactive graphical viewer and editor for tabular data, based on STIL APIs and implementing the STILTS functionalities. It provides flexible cross-matching criteria, such as coordinates, 2D or 3D (or more) Cartesian positions, match distance fixed or per-object, exact object, etc.

The CDS cross-match service (CDS-Xmatch)[6] [15] is a new data fusion and data management tool, which is used to efficiently cross-identify sources between very large catalogs (all VizieR tables, SIMBAD) or between a user-uploaded list of positions and a large catalog. Users could submit their cross-matching jobs through a Web interface, or directly following the UWS pattern. The results will be stored on the user personal storage space and backed up by iRODS.

ARCHES[7] [64], is the foundation for probabilistic multi-catalog cross-matching of unresolved sources. It aims to provide the international astronomical community with well-characterized multi-wavelength data in the form of spectral energy distributions (SEDs). Users can be accessed by using the http API that submits scripts on a dedicated machine.

Despite the considerable progress that has been made in astronomical catalog cross-matching, several issues deserve further investigations. Although the process of catalog cross-matching is similar to the join operation in database, the calculation

[5] http://www/starlink.ac.uk/topcat/

[6] http://cdsxmatch.u-strasbg.fr/xmatch/

[7] http://www.arches-fp7.eu

complexity is increased due to the calculation of the distance error between points to points. And as the amount of data produced by the telescope increases dramatically, existing methods can hardly maintain in high performance status. Therefore, timely and effective algorithms, techniques, and tools that have extremely scalability are in urgent need to cope with large scale of catalogs. Additionally, and importantly, existing methods mainly focus on point sources cross-matching. While in fact, there are many non-point sources such as quasar, which has a radio core in center and two radio lobes far away from the core. When cross-matching these objects, we also have to consider these two lobes to find their full information. In addressing such problems, manual matching is now mostly used which is unintelligent and time-consuming. Thus, it is a challenge to develop automatic and efficient cross-matching methods and tools for non-point sources in the future.

3 Multi-band astronomical image fusion

Astronomical images provide information about the great variety of celestial objects in the Universe, the physical processes taking place in it, and the formation and evolution of the cosmos [62]. Astronomical image fusion is the process of extracting useful information from source images taken by different telescopes or at different time, and integrated them into the fused image without introducing any artifact in the process. Based on the adopted fusion principles, the existing astronomical image fusion methods can be categorized into three major families: (1) the multi-scale transform-based methods; (2) the sparse representation-based methods; (3) the Bayesian-based methods. Table 4 is the summary of the main astronomical image fusion families, the adopted strategies, and the applied image types.

3.1 Multi-scale transform-based methods

Multi-scale transform-based methods constitute an active field in image fusion research. These methods are mainly organized in three stages: image transform, fusion of the transform coefficients, and inverse transform. In the field of astronomy, the most widely used multi-scale decomposition methods for image fusion are the pyramid and wavelet transform (WT). [26] proposed a fusion-detection algorithm of multi-wavelength astronomical images that was based on Laplacian pyramid analysis of the input images feeding a unique vectorial hierarchical hidden Markov model, and the iterative Van Cittert's algorithm was employed to the final reconstruction of the fused image. The images from four bands— optical, infrared, ultraviolet, and X-ray—were successfully fused by using their scheme. Later, Flitti et al. [27] extended their Laplacian pyramid decomposition based model by using a Gaussian scaling function. The Data likelihood was formulated using copulas theory as a multidimensional Generalized Gaussian density to deal with the Non-Gaussianity of coefficients of the multi-scale analysis.

The wavelet transforms is based on the decomposition of the image into multiple channels, provides a framework to decompose images into a number of new images, each one of them with a different resolution degree. The most used transform

Table 4 Major astronomical image fusion methods and applied image types

Different families of fusion	Ref.	Method	image type
Multi-scale transform-based	Bijaoui [11]	Multiple wavelet vision model	Optical
	Starck [75]	Curvelet transform, Ridgelet transform	Infrared
	Flitti et al. [26, 27]	Laplacian pyramid analysis	multi-band
	Ahmad et al. [3]	Undecimated dual tree complex wavelet transform (UDTCWT)	Infrared/Visible
	Abourayan et al. [2]	DWT, SWT, and UTCWT	N/A
Sparse representation-based	Bobin and Starck [13, 14]	Compressed sensing	Far-infrared and Sub-millimeter
	Zhou et al. [86]	Compressed sensing	Colored Sun images
Bayesian-based	Collet et al. [21]	Hierarchical Markovian model	Near-infrared: J,H,Ks
	Gutiérrez [34] and Jalobeanu [43]	Bayesian probabilistic model	Simulated Hyperspectral images
	Petremand et al. [69]	Bayesian framework	Simulated Hyperspectral images

is the stationary wavelet transform (SWT), also called 'à trous' algorithm, and discrete wavelet decomposition (DWT). Bijaoui [11] gave a tutorial of the wavelet-based transform methods, in which they present a comprehensive introduction to wavelet transform models adopted to astronomical images. And then, Bijaoui et al. [12] developed an automated fusion method for astronomical images that was based on a scale space decomposition with the redundant wavelet transform.

It is known that the DWT suffers from some fundamental shortcomings, e.g., shift variance, aliasing, and lack of directionality [84]. As a solution to these problems, the dual-tree complex wavelet transform (DT-CWT) proposed by [54] is introduced into image fusion. The key advantages of this method are its shift invariance and directional selectivity, which can reduce the artifacts. Later, Hill et al. [38] developed the undecimated dual-tree complex wavelet transform (UDT-CWT), which extends the traditional DT-CWT using the methods of filter upsampling and the removal of downsampling developed for the Undecimated Discrete Wavelet Transform (UDWT). Ahmad et al. [3] proposed an UDT-CWT based fusion scheme for astronomical images, and implemented scheme on fusing visible and infrared images. Abourayan et al. [2] implemented DWT, SWT, and DT-CWT methods on different computing methods, sequential, parallel, and cloud, and evaluated the fusion results of these methods on astronomical images.

Besides, Candes and Donoho [19, 20] proposed two new methods of multi-scale representation: curvelet and ridgelet transforms, which are very different from wavelet-like systems. Curvelets and ridgelets take the form of basic elements that exhibit high directional sensitivity and are highly anisotropic [76]. The ridgelet transform can effectively deal with line like phenomena in two dimensions, plane-like phenomena in three dimensions, etc. The idea of the curvelet transform is to first decompose the image into sub-bands, each scale is then analyzed by means of a local ridgelet transform. They have strong directional character in those elements that are highly anisotropic at fine scales. Hence, for specific astronomical data containing edges (planet surfaces, for example), curvelets are the best choice because they provide a mathematical representation that is ideally adapted to represent objects with curved shapes. For example, Starck et al. [76] applied curvelet transform and co-addition technique to the problem of restoring an astronomical image from noisy data, and compared the results with those obtained via well established methods based on the thresholding of wavelet coefficients. Then, Starck et al. proposed combinations of wavelets and ridgelets, and combinations of wavelets and curvelets, to fuse the astronomical objects in infrared.

3.2 Sparse representation-based methods

Unlike the image fusion methods based on multi-scale transform with prefixed basis functions, sparse representation-based methods work on the basis of the possible representation of images with linear combinations of sparse bases in over-complete dictionaries. Compressed sensing (CS) as a new field of interest based on sparsity has emerged recently and widely applied into astronomical images. Bobin and Starck [13, 14] treated CS as a new framework to handle multiple observations in the same field of viewing and recovering information at a very low signal-to-noise ratio, which is impossible with standard compression methods. Liu et al. [56] used random and sparse Fourier samples to reduce the amount of measurement samples, and lower the requirements of cost and complexity in telescope systems that rely on Fourier transforms for effective rapid imaging. Barbey et al. [5] successfully applied CS to real Herschel/PACS data, taking account of all the instrumental effects, and significantly improved the resolution of sky maps. Zhou et al. [86] proposed a new reconstruction algorithm for astronomical images based on CS techniques. They applied Daubechies orthogonal wavelets to obtain a sparse representation. A matrix representing a random Fourier ensemble was used to obtain a sparse representation in a lower dimensional space, and a novel minimum total variation with block adaptive sensing was used to reconstruct the colored Sun images.

3.3 Bayesian-based methods

The goal of Bayesian methods is to determine the probability of whether the data are objects or a background. In other words, the objective is to provide a probability map with higher values in the zones where an astronomical object is more likely to be located, and lower values in the zones that are more likely to be sky [62]. The Bayesian-based methods have been widely applied to astronomical image, because the fusion of astronomical targets requires images to be inferred from a number of blurred and noisy sources, possibly from different sensors under various conditions. These methods can recovery of a compound model ”image and uncertainties” that best relates to the observations, and contains a maximum of useful information from the initial dataset. Collet et al. [21] presented an unsupervised method to automatically segment and fuse multi-spectral astronomical images, which was based on integrating hierarchical segmentation results into Markov random field spatial prior in the Bayesian framework. The method was implemented on real astronomical images belong to near-infrared bands: J, H, and Ks.

In recent years, new generation integral-field spectrographs (IFS) such as MUSE are starting observing celestial objects with much higher spectral and spatial resolutions. The new hyperspectral observations will provide huge amount of scientific data whose analysis requires the development of dedicated processing methods. Thus, the bayesian-based methods are successfully and widely applied to hyperspectral image fusion. Gutièrrez [34] and Jalobeanu [43] developed a multi-source data fusion method that was based on a probabilistic framework and band-limited signal theory. A Bayesian inference scheme is used to invert a forward model, which describes the image formation process for each observation and takes into account some a priori knowledge. Jalobeanu et al. [44] extended the method developed in Jalobeanu [43] for the fusion of 2D images to 3D, which used a probabilistic approach allowing for optimal data fusion and uncertainty estimation at the same time. However, this algorithm focuses on small-size, simulated astronomical observations with varying parameters, and its application to the hyperspectral case is not straightforward due to the data complexity and the size which are critical parameters for Bayesian approaches. Petremand et al. [69] then improved the above algorithm and provided a fusion scheme performed in a sequential way, which allows to deal with large hyperspectral observations and acquisition parameters, but does not exempt algorithms and data structures from being designed, so as to minimize computing time and memory usage.

Astronomical image fusion presents problems similar to image fusion in other fields (e.g. in computer vision), which needs effective image information extraction and appropriate fusion principles. Nevertheless, there are some difficulties associated with astronomical image characteristic that make this task complicated. Many astronomical objects do not show clear boundaries and the noise, disturbance, variable background, source shape will also affect the feature extraction. Thus, more precise denoising procedures that specialized for astronomical images are required for clear visualization of the astronomical image. To achieve the best representation of the fused images, it is still challenging to select the optimum parameters and decomposition levels of the fusion algorithm. Hybrid image fusion approach that combines the advantages of different methods is also helped, the combination of them will make a good use of characteristics of both strengths for higher image quality and suitable processing time. Moreover, state-of-the-art deep learning techniques and CNN-based methods can be considered for astronomical image fusion, which have been specialized for image fusion in the other fields. Finally, qualitative evaluation metrics such as complexity, processing time, throughput, image quality, and other metrics should be established to provide an accurate estimation of the fusion algorithm performance.

4 Single source image mosaic

Astronomical images taken by Long-focus telescope usually have high precision and luminosity but small field of view. In order to obtain astronomical images with high resolution and a large field of view, image mosaics are implemented. Image mosaic is a method of image-processing wherein multiple images with overlapping parts are combined into a single seamless image. The main procedures of astronomical image mosaic include image registration, background matching, point source extraction, and creating mosaic images. A number of software packages have existed to construct astronomical mosaic for different kinds of telescopes, such as MOPEX (MOsaicker and Point source EXtractor), Montage, Drizzle, etc. (summarized in Table 5).

MOPEX [58, 59] is a software package for image mosaicking and point source extraction. It was developed for the Spitzer Space Telescope. MOPEX features the

Table 5 Major astronomical image mosaic software packages

Mosaicking tools	Ref.	Notes
MOPEX	Makovoz and Khan [58] and Makovoz et al. [59]	A mosaic package used in Spitzer Science Center
Montage	Berriman et al. [7] and Berriman et al. [52]	A part of the architecture of the National Virtual Observatory
	Berriman et al. [8]	A grid-enabled version of Montage
	Katz et al. [47] and Jacob et al. [42]	Details about Montage used as a grid portal
	De Prado et al. [22]	Montage used in cloud computing with proposed expert broker
SWarp	Bertin et al. [10]	A FITS images co-adder in French TERAPIX center
	Gwyn [35]	The MegaCam Image Stacking Pipeline using the SWarp
Drizzle	Fruchter and Hook [29]	An efficient means of combining dithered data taken by HST
	Takeda et al. [77]	Super-Drizzle—applied a kernel regression framework
	Fruchter [28]	iDrizzle—upgraded the previous Voronoi approximation
	Wang and Li [81]	fiDrizzle—an improvement of iDrizzle on computational speed
YourSky	Jacob et al. [40]	A custom astronomical image mosaicking software
	Jacob et al. [41]	An improvement of yourSky deployed on IPG
AWAIC	Masci and Fowler [61]	An image co-addition tool in WISE frame pipeline

use of several interpolation techniques, co-addition schemes, and robust and flexible outlier detection based on spatial and temporal filtering. A number of original algorithms have been designed and implemented in MOPEX. Among them is direct plane-to-plane coordinate transformation, which allows at least an order of magnitude speed up in performing coordinate transformation by bypassing the sky coordinates. The dual outlier detection makes possible outlier detection in the areas of even minimal redundancy. Image segmentation based on adaptive thresholding is used for object detection, which is part of outlier detection. Efficient use of computer memory allows mosaicking of datasets of very deep coverage of thousands of images per pointing, as well as areas of sky covering many square degrees. After the input images are interpolated to a common grid, they can be combined into a single mosaic image.

Montage [52] is a software system for generating astronomical image mosaics according to user-specified size, rotation, World Coordinate System (WCS) compliant projection and coordinate system, with background modeling and rectification capabilities. There are four steps to building a mosaic with Montage [7]: re-projection of input images to a common spatial scale and coordinate system; modeling of background radiation in images to achieve common flux scales and background levels; rectification of images to a common flux scale and background level; and co-addition of re-projected, background-corrected images into a final mosaic. Berriman et al. [8] provided a grid-enabled version of Montage, which is suitable for large scale processing of the sky. It exploits to the maximum the parallelization inherent in the Montage architecture, whereby image re-projections are performed in parallel. All the re-projection jobs can be added to a pool of tasks and performed by as many processors as are available. Some potential solutions to the problems in the initial grid implementations are described in the paper of [48]. The performance aspects of the methods for running Montage on the grid are evaluated in [47]. Jacob et al. [42] extended these previous publications by providing additional details about the Montage algorithms, architectures, and usage. Recently, De Prado et al. [22] were centered on reducing the execution time of Montage mosaics workflows in clouds through the application of a fuzzy rule-based broker as local scheduler in data centers. The fuzzy broker retrieves information of the state of the hosts virtual machines (VMs) in the data center where the mosaic images are to be executed, and it associates a fuzzy characterization that concerned the dynamism in the state. This method suggests the more suitable host VM for every job in the workflow using the considered fuzzy states and its expert knowledge or if-then rules.

SWarp is a program from the French TERAPIX center that resamples and co-adds together FITS images using any arbitrary astrometric projection defined in the WCS standard [9]. Based on the astrometric and photometric calibrations derived in [10] at an earlier phase of the pipeline, SWarp re-maps the pixels to a perfect projection system, and co-adds them in an optimum way, according to their relative weights. Later, Gwyn [35, 36] developed a MegaPipe image processing pipeline, which combined multiple images from the MegaCam mosaic camera on Canada-France-Hawaii Telescope (CFHT) and combined them into a single output image. The calibrated images are co-added using the program SWarp in the pipeline.

In order to combine the irregularly sampled data from the Hubble Deep Field HDF, a new image mosaic algorithm, Drizzle was developed. It preserves photometry and resolution, can weight input images according to the statistical significance of each pixel, and removes the effects of geometric distortion both on image shape and photometry [29]. The method can be categorized as spatially adaptive filters which make use of linear combinations of pixels in a local neighborhood to de-noise or reconstruct a pixel at a desired position. The Drizzle algorithm was developed with small, faint, partially resolved sources in mind, thus, it is not pretty suitable for high signal-to-noise unresolved objects. Takeda et al. [77] then proposed a Super-Drizzle algorithm which improved the quality of reconstruction of the drizzle algorithm. They exploit the kernel regression framework [78] to justify a powerful variation of the drizzle algorithm with superior performance, applicable to both regularly and irregularly sampled data. Fruchter [28] presented a new method for creating band-limited images from undersampled data, iDrizzle (iterative Drizzle), which upgraded the previous Voronoi approximation to the iDrizzle by replacing the value of nearest neighbor with that of Drizzle in the iterative Voronoi approximation, and introduced the over sampling— low pass filtering—interpolating process to the image co-adding procedure. Due to the iterative signal extraction and low pass filtering in frequency domain, iDrizzle achieved much better performance of de-convolving the pixelation of undersampled features than the super-Drizzle in small scale. Wang and Li [81] proposed a fiDrizzle algorithm, which made an improvement of iDrizzle on effectiveness and computational speed.

The yourSky [40] is a custom access astronomical image mosaicking software, which enables on the fly mosaicking to meet user-specified criteria for region of the sky to be mosaicked, datasets to be used, resolution, coordinate system, projection, data type and image format. It is a fully automated end-to-end software that handles all aspects of the mosaic construction including management of mosaic requests, management of a data cache for both input image plates and output mosaics, image mosaic construction on a multiprocessor system, etc. Then, the same research group [41] proposed the yourSkyG, an improved mosaicking software of yourSky. The yourSky requires use of a local multiprocessor system, while yourSkyG is capable of launching its computations on remote computers organized in a computational grid such as Information Power Grid (IPG). It allows to construct multiple mosaic on the grid with high throughput.

AWAIC [61] is an astronomical image co-adder to support the creation of a digital Image Atlas from the multiple frame exposures acquired with the Wide-field Infrared Survey Explorer (WISE). It includes preparatory steps such as frame background matching and outlier detection using robust frame-stack statistics. Frame co-addition is based on using the detector's Point Response Function (PRF) as an interpolation kernel. This kernel reduces the impact of prior-masked pixels; enables the creation of an optimal matched filtered product for point source detection; and it allows for resolution enhancement to yield a model of the sky that is consistent with the observations to within measurement error. The HiRes functionality allows for non-isoplanatic PRFs, prior noise-variance weighting, uncertainty estimation, and includes a ringing-suppression algorithm. It is generic for use on any astronomical image data that supports the FITS and WCS standards.

Nowadays, these mosaic packages are widely used by individuals on their local machines and clusters to perform research, or integrate them into work flows and pipelines to create new data products. For astronomers, however, astronomical image mosaic is more likely to be used to generate the image of the whole sky, so it often requires numerous sky area images and even years of images, which bring tremendous computing workload. In follow-on work, processing large-scale image mosaic on remote servers, or other methods that can ensure the accuracy but reduce the time consumption of mosaic are worth of further investigations.

5 Virtual observatory

The methods of preservation and management of astronomical data are different in various countries, and there are also great differences in different historical periods. Although the released astronomical data are freely shared worldwide, the diversity of data structure and storage affects the extraction and use of these data by astronomers. Thus, a number of national observatories have developed uniform data access and data discovery services that can be used across all datasets on-line, namely, Virtual Observatories (VOs) [23]. The standardization of VOs enables astronomers to interrogate multiple data centers in a seamless and transparent way, and gives data centers a framework for publishing and delivering services using their data. What's more, the establishment of VOs makes it convenient for fusing astronomical data across the globe.

In 2002, the International Virtual Observatory Alliance (IVOA) was created, with the main objective of defining standards to produce synergy and interoperability between the VO members [4]. Since its inception, the IVOA has already facilitated the establishment of a new international and widely accepted format for astronomical data (VOTable) and has defined essential standards for service registries, unified content descriptions (UCDs), data access (Catalogues, Images, Spectra, etc.), data models, query languages to access distributed databases, etc. The standards are still evolving, and the most recent information can be accessed in IVOA web site.[8]

The IVOA architecture only provides a general framework and standards that its members should follow, but each VO develop their own services based on their own goals. Up to now, IVOA had grown up to 21 members in the 5 continents (as shown in Table 6), each members share knowledge between them and the community in a standardized manner.

With the advent of MMA era, the demands on the VOs will get more pressing. Although IVOA is helpful, it is not enough to build a new field. The alliance intends to share the astronomical data between them and the community in a standardized manner, but several VOs have not accepted or updated the standards of their apparatus and projects. This is due to the lack of common tools for different bands of data or devices, which makes it difficult for VOs to normalize the data into a uniform format. Thus, in computer technology, it requires easily-deployed, flexible platforms and powerful tools to promptly transform and standardize the multi-messenger datasets

[8] http://www.ivoa.net/

Table 6 IVOAs members by year of affiliation and their websites

Project	Year	URL
Aus-VO (Australia)	2002	http://aus-vo.org.au/
AstroGrid (UK)	2002	http://www.astrogrid.org/
CVO (Canada)	2002	http://cadc-ccda.hia-iha.nrc-cnrc.gc.ca/
EURO-VO (European)	2002	http://www.euro-vo.org/
GAVO (German)	2002	http://www.g-vo.org/
RVO (Russia)	2002	http://www.inasan.rssi.ru/eng/rvo/
US-VAO (USA)	2002	http://www.usvao.org/
VO-France (France)	2002	http://www.france-vo.org/
VO-India (India)	2002	http://vo.iucaa.ernet.in/voi/
China-VO (China)	2003	http://www.china-vo.org/
HVO (Hungary)	2003	http://hvo.elte.hu/en/
JVO (Japan)	2003	http://jvo.nao.ac.jp/
VObs.it (Italy)	2003	http://vobs.astro.it/
SVO (Spain)	2005	http://svo.cab.inta-csic.es/
ArVO (Armenia)	2006	http://www.aras.am/Arvo/arvo.htm
BRAVO (Brazil)	2009	http://www.lna.br/bravo/
NOVA (Argentina)	2011	http://nova.conicet.gov.ar/
UkrVO (Ukraine)	2011	http://www.ukr-vo.org/
ChiVO (Chile)	2013	http://www.chivo.cl/
SA^3 (South Africa)	2013	http://www.sa3.ac.za/

that are heterogeneous and distributed, to truly achieve seamless and transparent access and analysis of datasets across the world.

6 Conclusion and future directions

Astronomical data fusion has attracted considerable attention and made significant progress in the past few decades. With the advent of the MMA, it is possible to collect and process data from a number of new sources, thus requires fusion innovations to converge new astrophysical observation and existing datasets. However, the existing fusion methods are not included in the surveys related to astronomical data. We are the first to comprehensively overview the relevant fusion methods and applications, including astronomical catalog, astronomical image fusion, image mosaic, and virtual observatory. Moreover, we deliver insightful prospects for future work in these four areas, respectively.

Despite the considerable progress that has been achieved in astronomical data fusion, several issues remain for future work. The high-variety character of multi-messenger astronomical data requires the institute to maintain a strong standard of managing and analyzing data, and the unified interface to bridge the gaps between multiple sources. Easily-deployed and flexible tools to transform and standardize the heterogeneous multi-messenger datasets are required. Considering the exponential growth of observation data, a sustainable, long-term storage archive manager will be needed that capable of dynamical updates and heterogeneous datasets. Further, MMA's big-data character requires developing new scaling of algorithms, models, and techniques to process large datasets in different formats in a timely and effective manner, taking advantages of cloud computing and virtualization technology to handle massive data streams, so as to fully realize the promise of this new era.

In conclusion, the recent progress achieved in astronomical data fusion exhibits a promising trend in this field with a huge potential for future improvement. The authors expect that this research could be a useful starting point for newer approaches and a helpful contribution in the field of astronomical data fusion.

Acknowledgements This work is supported by the Joint Research Fund in Astronomy (U1731243, U1731125, U1531111) under cooperative agreement between the National Natural Science Foundation of China (NSFC) and Chinese Academy of Sciences (CAS), the National Natural Science Foundation of China (11573019, 61602336).

References

1. Abbott, B.P., Abbott, R., Abbott, T.D., et al.: Gw170817: Observation of gravitational waves from a binary neutron star inspiral. Phys. Rev. Lett. **119**, 161101 (2017)
2. Abourayan, M., Jamali, M.M., Schmidt, V.: Image fusion of astronomical images via parallel/cloud processing. In: Aerospace and Electronics Conference, pp. 100–104 (2017)
3. Ahmad, A., Riaz, M.M., Ghafoor, A., Zaidi, T.: An improved infrared/visible fusion for astronomical images. Adv. Astron. **2015**(6), 65–72 (2015)
4. Araya, M., Solar, M., Antognini, J.: A brief survey on the virtual observatory. New Astron. **39**, 46–54 (2015)
5. Barbey, N., Sauvage, M., Starck, J.L., Ottensamer, R., Chanial, P.: Feasibility and performances of compressed-sensing and sparse map-making with herschel/pacs data. Astron. Astrophys. **527**(4–6361), 307–316 (2010)
6. Becla, J., Lim, K.T., Monkewitz, S., Nietosantisteban, M., Thakar, A., U, J.H.: Organizing the extremely large lsst database for real-time astronomical processing. Office of Scientific and Technical Information Technical Reports (2007)
7. Berriman, G.B., Curkendall, D., Good, J.C., Jacob, J.C., Katz, D.S., Kong, M., Monkewitz, S., Moore, R., Prince, T.A., Williams, R.E.: Architecture for access to a compute-intensive image mosaic service in the nvo. Virtual Observ. **4846**, 91–102 (2002)
8. Berriman, G.B., Deelman, E., Good, J.C., Jacob, J.C., Katz, D.S., Kesselman, C., Laity, A.C., Prince, T.A., Singh, G., Su, M.H.: Montage: A grid-enabled engine for delivering custom science-grade mosaics on demand. In: Optimizing Scientific Return for Astronomy through Information Technologies, procspie, vol. 5493, pp. 221–232 (2004)
9. Bertin, E.: Swarp: Resampling and co-adding fits images together. Astrophysics Source Code Library (2010)
10. Bertin, E., Mellier, Y., Radovich, M., Missonnier, G., Didelon, P., Morin, B.: The TERAPIX Pipeline. In: Astronomical Data Analysis Software and Systems XI, Astronomical Society of the Pacific Conference Series, vol. 281, p. 228 (2002)
11. Bijaoui, A.: A multiscale vision model adapted to the astronomical images. Signal Process. **46**(3), 345–362 (1995)
12. Bijaoui, A., Bobichon, Y., Vandame, B.: Multiscale image fusion in astronomy. Vistas Astron. **41**(3), 365–372 (1997)
13. Bobin, J., Starck, J.L.: Compressed sensing in astronomy. IEEE J. Selected Topics Signal Process. **2**(5), 718–726 (2008)

14. Bobin, J., Starck, J.L.: Compressed sensing in astronomy and remote sensing: A data fusion perspective. In: Wavelets XIII, vol. 7446, p. 74460I (2009)
15. Boch, T., Pineau, F., Derriere, S.: The CDS cross-match service. In: Astronomical Data Analysis Software and Systems XXI, Astronomical Society of the Pacific Conference Series, vol. 461, pp. 291–294 (2012)
16. Budavari, T., Lee, M.A.: Cross-identification of astronomical catalogs on multiple gpus. In: Astronomical Data Analysis Software and Systems XXII, vol. 475, p. 235 (2013)
17. Budavari, T., Lee, M.A.: Xmatch: Gpu enhanced astronomic catalog cross-matching. Astrophysics Source Code Library, p. 03021 (2013)
18. Budavári, T., Szalay, A.S.: Probabilistic cross-identification of astronomical sources. APJ **679**, 301–309 (2008)
19. Candes, E.J., Donoho, D.L.: Curvelets, multiresolution representation, and scaling laws. In: Wavelet Applications in Signal and Image Processing VIII, vol. 4119, pp. 1–12 (2000)
20. Candes, E.J., Donoho, D.L.: Curvelets and curvilinear integrals. J. Approx. Theory **113**(1), 59–90 (2001)
21. Collet, C., Louys, M., Provost, J.N., Obero, A.: Fusion of astronomical multiband images on a markovian quadtree. In: International Conference on Information Fusion, pp. 396–403 (2002)
22. De Prado, R.P., Garcia-Galan, S., Exposito, J.E.M., Lopez, L.R.L., Reche, R.R.: Processing astronomical image mosaic workflows with an expert broker in cloud computing. Image Process. Commun. **19**(4), 5–20 (2014)
23. Djorgovski, S.G., Williams, R.: Virtual observatory: From concept to implementation. In: From Clark Lake to the Long Wavelength Array: Bill Erickson's Radio Science, Astronomical Society of the Pacific Conference Series, vol. 345, p. 517 (2005)
24. Fan, D., Budavári, T., Szalay, A.S., Cui, C., Zhao, Y.: Efficient catalog matching with dropout detection. Publ. Astron. Soc. Pacific **125**(924), 218–223 (2013)
25. Fan, D., Budav, S.T.R., Norris, P.R., Hopkins, M.A.: Matching radio catalogues with realistic geometry: Application to swire and atlas. Mon. Not. R. Astron. Soc. **451**(2), 1299–1305 (2015)
26. Flitti, F., Collet, C., Slezak, E.: Wavelet domain astronomical multiband image fusion and restoration using markov quadtree and copulas. In: Signal Processing Conference, 2005 European, pp. 1–4 (2005)
27. Flitti, F., Collet, C., Slezak, E.: Image fusion based on pyramidal multiband multiresolution markovian analysis. Signal Image Video Process. **3**(3), 275–289 (2009)
28. Fruchter, A.S.: A new method for band-limited imaging with undersampled detectors. PASP **123**, 497 (2011). 1102.0292
29. Fruchter, A.S., Hook, R.N.: Drizzle: A method for the linear reconstruction of undersampled images. Publ. Astron. Soc. Pac. **114**(792), 144–152 (1998)
30. Gorski, K.M., Hivon, E., Banday, A.J., et al.: Healpix: A framework for high-resolution discretization and fast analysis of data distributed on the sphere. Astrophys. J. **622**(2), 759–771 (2005)
31. Gray, J., Nieto-Santisteban, M.A., Szalay, A.S., Thakar, A.R., Fekete, G., O'Mullane, W., Heber, G., Rots, A.H.: There goes the neighborhood: Relational algebra for spatial data search. Computer Science (2004)
32. Gray, J., Nieto-Santisteban, M.A., Szalay, A.S.: The zones algorithm for finding points-near-a-point or cross-matching spatial datasets. Microsoft Research (2007)
33. Greene, G., Budavari, T., Li, N., Nietosantisteban, M., Szalay, A., Thakar, A.: Chapter 13: Web-based tools - open skyquery: Distributed database queries and crossmatching. In: The National Virtual Observatory: Tools and Techniques for Astronomical Research, vol. 382, p. 111 (2007)
34. Gutièrrez, J.A.: Multisource data fusion for bandlimited signals: A bayesian perspective. In: American Institute of Physics, vol. 872, pp. 391–400 (2006)
35. Gwyn, S.D.J.: MegaPipe: The MegaCam image stacking pipeline at the canadian astronomical data centre. PASP **120**, 212 (2008)
36. Gwyn, S.D.J.: The canada-france-hawaii telescope legacy survey: Stacked images and catalogs. Astron. J. **143**(2), 38 (2012)
37. Han, B., Zhang, Y.X., Zhong, S.B., Zhao, Y.H.: Astronomical data fusion tool based on PostgreSQL. Res. Astron. Astrophys. **16**, 178 (2016)
38. Hill, P., Achim, A., Bull, D.: The undecimated dual tree complex wavelet transform and its application to bivariate image denoising using a cauchy model. In: IEEE International Conference on Image Processing, pp. 1205–1208 (2012)

39. Icecube, T., HES, S., Telescope, L., Teams, V.: Multi-messenger observations of a flaring blazar coincident with high-energy neutrino icecube-170922a. Science **361**, 6398 (2018)
40. Jacob, J.C., Brunner, R.J., Curkendall, D.W., Djorgovski, S.G., Good, J.C., Husman, L., Kremenek, G., Mahabal, A.: YourSky: Rapid desktop access to custom astronomical image mosaics. In: Virtual Observatories, Procspie, vol. 4846, pp. 53–64 (2002)
41. Jacob, J.C., Collier, J.B., Craymer, L.G., Curkendall, D.W.: yourskyg: Large-scale astronomical image mosaicking on the information power grid. Scalable Comput. Pract. Exper. **1**, 59–75 (2006)
42. Jacob, J.C., Katz, D.S., Berriman, G.B., Good, J., Laity, A.C., Deelman, E., Kesselman, C., Singh, G., Su, M.H., Prince, T.A., Williams, R.: Montage: A grid portal and software toolkit for science-grade astronomical image mosaicking. ArXiv e-prints (2010)
43. Jalobeanu, A.: Multi-source data fusion and super-resolution from astronomical images. In: Statistical Challenges in Modern Astronomy IV, vol. 371, p. 419 (2007)
44. Jalobeanu, A., Petremand, M., Collet, C.: Bayesian fusion of hyperspectral astronomical images. In: American Institute of Physics Conference Series, American Institute of Physics Conference Series, vol. 1305, pp. 295–302 (2011)
45. Jia, X., Luo, Q.: Multi-assignment single joins for parallel cross-match of astronomic catalogs on heterogeneous clusters. In: Proceedings of the 28th International Conference on Scientific and Statistical Database Management, pp. 1–12 (2016)
46. Jia, X., Luo, Q., Fan, D.: Cross-matching large astronomical catalogs on heterogeneous clusters. In: IEEE 21st International Conference on Parallel and Distributed Systems, pp. 617–624 (2015)
47. Katz, D.S., Jacob, J.C., Berriman, G.B., Good, J., Laity, A.C., Deelman, E., Kesselman, C., Singh, G.: A comparison of two methods for building astronomical image mosaics on a grid. In: Proceedings of the International Conference on Parallel Processing Workshops, pp. 85–94 (2005)
48. Katz, D.S., Anagnostou, N., Berriman, B.G., Deelman, E., Good, J., Jacob, J.C., Kesselman, C., Laity, A., Prince, T.A., Singh, G.: Astronomical image mosaicking on a grid: Initial experiences. Engineering The Grid - Status and Perspectives (2006)
49. Koposov, S., Bartunov, O.: Q3C, quad tree cube – the new sky-indexing concept for huge astronomical catalogues and its realization for main astronomical queries (cone search and Xmatch) in open source database PostgreSQL. In: Astronomical Data Analysis Software and Systems XV, Astronomical Society of the Pacific Conference Series, vol. 351, p. 735 (2006)
50. Kumar, V.S., Kurc, T., Saltz, J., Abdulla, G., Kohn, S.R., Matarazzo, C.: Architectural implications for spatial object association algorithms. In: IEEE International Symposium on Parallel and Distributed Processing, pp. 1–12 (2009)
51. Kunszt, P.Z., Szalay, A.S., Thakar, A.R.: The Hierarchical Triangular Mesh, pp. 631–637. Springer, Berlin (2001)
52. Laity, A.C., Anagnostou, N., Berriman, G.B., Good, J.C., Jacob, J.C., Katz, D.S., Prince, T.: Montage: An astronomical image mosaic service for the NVO. In: Astronomical Data Analysis Software and Systems XIV, Astronomical Society of the Pacific Conference Series, vol. 347, p. 34 (2005)
53. Landais, G., Ochsenbein, F., Simon, A.: TAPVizieR: A new way to access the VizieR database. In: Astronomical Data Analysis Software and Systems XXII, Astronomical Society of the Pacific Conference Series, vol. 475, p. 227 (2013)
54. Lewis, J.J., O'Callaghan, R.J., Nikolov, S.G., Bull, D.R., Canagarajah, N.: Pixel- and region-based image fusion with complex wavelets. Inf. Fus. **8**(2), 119–130 (2007)
55. Li, L., Tang, D., Liu, T., Liu, H., Li, W., Cui, C.: Optimizing the join operation on hive to accelerate cross-matching in astronomy. In: Parallel and Distributed Processing Symposium Workshops, pp. 1735–1745 (2014)
56. Liu, X.Y., Dong, L., Wang, J.L.: Fourier telescop imaging via sparse sampling. Opt. Precis. Eng. **18**(3), 521–527 (2010)
57. Ma, X., Du, Z., Sun, Y., Bai, Y., Wu, S., Tchernykh, A., Xu, Y., Wu, C., Wei, J.: E-zone: A faster neighbor point query algorithm for matching spacial objects. In: International Conference on Computational Science, pp. 473–479 (2018)
58. Makovoz, D., Khan, I.: Mosaicking with mopex. In: Astronomical Data Analysis Software and Systems XIV, Astronomical Society of the Pacific Conference Series, vol. 347, p. 81 (2005)
59. Makovoz, D., Roby, T., Khan, I., Booth, H.: MOPEX: A software package for astronomical image processing and visualization. In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, procspie, vol. 6274, p. 62740C (2006)

60. Malik, T., Szalay, A.S., Budavari, T., Thakar, A.R.: Skyquery: A webservice approach to federate databases. arXiv:cs/0211023 (2002)
61. Masci, F.J., Fowler, J.W.: AWAIC: A WISE astronomical image co-adder. In: Astronomical Data Analysis Software and Systems XVIII, Astronomical Society of the Pacific Conference Series, vol. 411, p. 67, 0812.4310 (2009)
62. Masias, M., Freixenet, J., Lladó, X., Peracaula, M.: A review of source detection approaches in astronomical images. Mon. Not. R. Astron. Soc. **422**(2), 1674–1689 (2012)
63. Mi, C., Chen, Q., Liu, T.: An efficient cross-match implementation based on directed join algorithm in mapreduce. In: Proceedings of the 2011 Fourth IEEE International Conference on Utility and Cloud Computing, IEEE Computer Society, UCC '11, pp. 41–48 (2011)
64. Motch, C., Carrera, F., Genova, F., et al.: The arches project. In: Astronomical Data Analysis Software and Systems XXV, Astronomical Society of the Pacific Conference Series, vol. 512, p. 165 (2017)
65. Nietosantisteban, M.A., Thakar, A.R., Szalay, A.S.: Cross-matching very large datasets. Astronomy (2006)
66. Nietosantisteban, M.A., Thakar, A.R., Szalay, A.S., Gray, J.: Large-scale query and xmatch, entering the parallel zone. In: Astronomical Data Analysis Software and Systems XV, Astronomical Society of the Pacific Conference Series, vol. 351, p. 493 (2007)
67. Ochsenbein, F., Bauer, P., Marcout, J.: The vizier database of astronomical catalogues. Astron. Astrophys. Suppl. **143**(1), 23–32 (2000)
68. Peng, D.U., Ren, J.J., Pan, J.C., Luo, A.: New cross-matching algorithm in large-scale catalogs with threadpool technique. Sci. Chin: Phys. Mech. Astron. **57**(3), 577–583 (2014)
69. Petremand, M., Jalobeanu, A., Collet, C.: Optimal bayesian fusion of large hyperspectral astronomical observations. Statist. Methodol. **9**(1a2), 44–54 (2012)
70. Pineau, F., Boch, T., Derriere, S.: Efficient and scalable cross-matching of (very) large catalogs. In: Astronomical Data Analysis Software and Systems XX, Astronomical Society of the Pacific Conference Series, vol. 442, p. 85 (2011)
71. Pineau, F.X., Derriere, S., Motch, C., Carrera, F.J., Genova, F., Michel, L., Mingo, B., Mints, A., Nebot Gómez-Morán, A., Rosen, S.R., Ruiz Camuñas, A.: Probabilistic multi-catalogue positional cross-match. AAP **597**, A89 (2017)
72. Riccio, G., Brescia, M., Cavuoti, S., et al.: C^3, a command-line catalog cross-match tool for large astrophysical catalogs. Publ. Astron. So. Pac. **129**(972), 024005 (2017)
73. Salvato, M., Buchner, J., Budavari, T., Dwelly, T., Merloni, A., Brusa, M., Rau, A., Fotopoulou, S., Nandra, K.: Finding counterparts for all-sky x-ray surveys with nway: A bayesian algorithm for cross-matching multiple catalogues. Mon. Not. R. Astron. Soc. **473**, 4937–4955 (2017)
74. Soumagnac, M.T., Ofek, E.O.: catshtm: A tool for fast accessing and cross-matching large astronomical catalogs. PASP **130**(7), 075002 (2018)
75. Starck, J.L.: Multiscale methods in astronomy: Beyond wavelets. Astron. Data Anal. Softw. Syst. **XI**(281), 391 (2002)
76. Starck, J.L., Donoho, D.L., CandÃšs, E.J.: Astronomical image representation by the curvelet transform. Astron. Astrophys. **398**(2), 785–800 (2002)
77. Takeda, H., Farsiu, S., Christou, J., Milanfar, P.: Super-drizzle: Applications of adaptive kernel regression in astronomical imaging. in: The Advanced Maui Optical and Space Surveillance Technologies Conference, p. E27 (2006)
78. Takeda, H., Farsiu, S., Milanfar, P.: Kernel regression for image processing and reconstruction. IEEE Trans. Image Process. **16**(2), 349–366 (2007)
79. Taylor, M.: Topcat – tool for operations on catalogues and tables. Starlink User Note, p. 253 (2011)
80. Taylor, M.B.: STILTS - a package for command-line processing of tabular data. In: Astronomical Data Analysis Software and Systems XV, Astronomical Society of the Pacific Conference Series, vol. 351, p. 666 (2006)
81. Wang, L., Li, G.L.: How to co-add images? I. A new iterative method for image reconstruction of dithered observations. Res. Astron. Astrophys. **17**, 100 (2017)
82. Wang, S., Zhao, Y., Luo, Q., Wu, C., Yang, X.: Accelerating in-memory cross match of astronomical catalogs. In: IEEE International Conference on E-Science, pp. 326–333 (2013)
83. Wenger, M., Ochsenbein, F., Egret, D., et al.: The simbad astronomical database. The cds reference database for astronomical objects. Astron. Astrophys. Suppl. **143**(1), 9–22 (2000)
84. Zhang, Z., Blum, R.: A categorization of multiscale-decomposition-based image fusion schemes with a performance study for a digital camera application. Proc. IEEE **87**(8), 1315–1326 (1999)

85. Zhao, Q., Sun, J., Yu, C., et al: A paralleled large-scale astronomical cross-matching function. In: Proceedings of the 9th International Conference on Algorithms and Architectures for Parallel Processing, pp. 604–614 (2009)
86. Zhou, W.P., Li, Y., Liu, Q.S., Wang, G.D., Liu, Y.: Fast compression and reconstruction of astronomical images based on compressed sensing. Res. Astron. Astrophys. **9**, 1207–1214 (2014)
87. Zhu, H.J., Han, B.C., Qiu, B.: Survey of Astronomical Image Processing Methods. Springer International Publishing (2015)