The transcription factor Spores Absent A is a PKA dependent inducer of *Dictyostelium* sporulation

Yoko Yamada, Andrew Cassidy & Pauline Schaap

Spores Absent A is a PKA dependent inducer of *Dictyostelium* sporulation

Sporulation in *Dictyostelium* fruiting bodies evolved from amoebozoan encystation with both being induced by cAMP acting on PKA, but with downstream components still being unknown. Using tagged mutagenesis to find missing pathway components, we identified a sporeless mutant defective in a nuclear protein, SpaA. Expression of prespore genes was strongly reduced in spaA- cells, while expression of many spore stage genes was absent. Chromatin immunoprecipitation (ChIP) of a SpaA-YFP gene fusion showed that (pre)spore gene promoters bind directly to SpaA, identifying SpaA as a transcriptional regulator. SpaA dependent sporulation gene expression required PKA in vivo and was stimulated in vitro by the membrane-permeant PKA agonist 8Br-cAMP. The PKA agonist also promoted SpaA binding to (pre)spore promoters, placing SpaA downstream of PKA. Sequencing of SpaA-YFP ChIPed DNA fragments revealed that SpaA binds at least 117 (pre)spore promoters, including those of other transcription factors that activate some spore genes. These factors are not in turn required for spaA expression, identifying SpaA as the major transcriptional inducer of sporulation.

Most free-living protists differentiate individually into dormant cysts or spores when challenged by environmental stress. In the Dictyostelia this transition evolved into a multicellular life style that culminates into the formation of fruiting bodies that carry the spores aloft. cAMP crucially regulates this process both as a secreted signal inducing chemotactic aggregation of starving amoebas and expression of aggregation genes and prespore genes, and as an intracellular messenger acting on PKA to induce maturation of spore and stalk cells. Comparative evolutionary studies revealed that these roles of cAMP are derived from a second messenger role of cAMP in stress-induced encystation in the unicellular amoebozoan ancestor. The adenylate cyclase AcrA and the cAMP phosphodiesterase RegA critically regulate intracellular cAMP levels in *D. discoideum*, with RegA activity being controlled by multiple sensor histidine kinases. In *D. discoideum* the sensor histidine kinases detect signals within the fruiting body that regulate the transition from motile amoebas into encapsulated spore and stalk cells at the correct time and place. AcrA, RegA and PKA also control encystation of solitary amoebas and sensor histidine kinases are abundant in their genomes, acting here as likely sensors for environmental stimuli.

At present, we have limited information of processes that occur downstream of PKA. Three transcription factors, CudA, BzpF and SrfA were shown to regulate prespore and spore-specific gene expression. CudA promotes expression of prespore genes in the slug, while BzpF and SrfA act later to induce subsets of spore-specific genes. BzpF null mutants initially form walled spores, but these spores disintegrate while still in the spore head. SrfA null mutants have defects in morphogenesis and form spherical instead of elliptical spores, with diminished viability. The expression of both BzpF and SrfA is upregulated by PKA, but they are not targets for phosphorylation by PKA. Loss of a fourth transcription factor, StkA causes prespore cells to transdifferentiate into stalk cells. Transdifferentiation does not occur in mutants that cannot activate PKA in prespore cells, such as *acbA*, *acrA*, and *psA::PKARm*, which just leave the prespore cells amoeboid and unencapsulated, indicating that StkA regulates a different developmental choice.

To identify missing components in the sporulation pathway, we used an insertional mutagenesis approach on cells transformed with a fusion construct of the spore coat gene *cotC* and monomeric red fluorescent protein.
Results
Identification of a transcription factor essential for spore formation. To identify unknown components in the *D. discoideum* sporulation pathway, we performed REMI mutagenesis and screened for mutants with defects in prespore or spore differentiation. To visualise these processes, we generated a strain in which the red fluorescent protein mRFPmars14 was fused to the 3′ end of the spore gene cotC. CotC protein accumulates in Golgi-derived prespore vesicles (PSVs) in slugs and is exocytosed at spore maturation to become incorporated in the spore coat15 and this was also the case for cotC-mRFP (Fig. 1B). REMI mutagenesis of Aa2/cotC-mRFP yielded a mutant, b39, with strongly reduced RFP fluorescence in the slugs and spore heads (Fig. 1A). Its prespore cells still showed weakly stained PSVs, but PSV exocytosis in spores was incomplete (Fig. 1B).

Sequencing of the amplified region that flanked the plasmid insertion site showed that insertion occurred at a DpnII site in gene DDB_G0287317, which encodes a cudA-like transcription factor.

We named the gene *SpaA* for spores absent A. The *D. discoideum* genome contains five genes homologous to *cudA*, and a *cudA* homolog is also present in *Entamoeba*24,25. SpaA has homologs in genomes representative of the four major groups of Dictyostelia17–19, which are more closely related to SpaA than to the other *D. discoideum* *cudA*-like genes (Fig. 1C), and are therefore likely SpaA orthologs. Alignment of SpaA with CudA and the SpaA orthologs in other Dictyostelia shows that the conserved core region of the *Entamoeba* *cudA* genes (Fig. 1C), and are therefore likely SpaA orthologs. Alignment of SpaA with CudA and the SpaA orthologs in other Dictyostelia shows that the conserved core region of the *Entamoeba* *cudA* and Dictyostelium *CudA* is present in all SpaA orthologs (Supplementary Fig. S1). Two 3- and 5 amino-acid sections of this region, which, when mutated in *Entamoeba* *CudA*, reduce DNA binding25, are well conserved in all SpaA orthologs. We assume from its homology to CadA that SpaA is also a DNA binding protein.

To confirm that the sporulation defective phenotype of the REMI mutant was due to a lesion in *spaA*, we generated a *spaA* null mutant by deleting part of the SpaA DNA binding region (Supplementary Fig. S2). The *spaA*-cells developed normally into migrating slugs and fruiting bodies (Fig. 1D,E). However, as observed with REMI mutant b39, the spore heads of the *spaA*- mutant were more "glassy" than the "milky" wild-type spore heads, and contained only round and phase dark cells (Fig. 1E,F). Antibodies against intact spores stain PSVs in prespore cells, or the wall of spores20. However, the *spaA*-spores showed both peripheral staining and granular staining inside the cells, most likely PSVs. Wild-type spores become strongly fluorescent when stained with Calcofluor, a reagent that interacts with cellulose, but the *spaA*-spores were only weakly fluorescent (Fig. 1F). It therefore appears that *spaA*-cells pass partially through PSV exocytosis, but never form cellulose containing spore walls. Unlike wild-type spores, the *spaA*-spores lysed when incubated with detergent, regardless of the time passed after fruiting bodies had matured (Fig. 1G).

SpaA localization and cell autonomous function. Data retrieved from genome-wide developmental gene expression profiles18 show that *spaA* transcription is strongly upregulated from 8–24 h of development and that transcripts are highly prespore-enriched (Supplementary Fig. S3A,B). To analyse localization of SpaA protein in both cells and multicellular structures, *spaA*, inclusive of its promoter, was fused to YFP and transformed into *spaA*-cells. A protein of the expected size of 92 kD was detected by Western analysis (Supplementary Fig. S3C) and the expression of *spaA*-SpaA_YFP in *spaA*-cells rescued spore formation, indicating that *SpaA_YFP* is functional (Supplementary Fig. S3D). Conform to the prespore enrichment of *spaA* mRNA, *SpaA_YFP* protein was expressed in the prespore region of slugs (Supplementary Fig. S3E). *SpaA_YFP* co-localized with the DNA stain DAPI in the nuclei of cells (Supplementary Fig. S3F) at all developmental stages where the protein was expressed. This localization is consistent with a role of SpaA in gene regulation.

SpaA expression in prespore nuclei suggests that SpaA has a cell-autonomous role in spore differentiation. To test this, we mixed the *spaA*-REMI mutant, which carried the cotC:mRFP marker, at different ratios with wild-type cells. The mRFP positive *spaA*-cells were readily incorporated into the spore head, but never differentiated into normal spores (Supplementary Fig. S3G). Using the recapitulated *spaA*-strain, we determined the contribution of detergent resistant spores to chimeric fruiting bodies as percentage of the initial number of plated cells (Supplementary Fig. S3H). Wild-type Aa2, developed alone, produced more than 100% spores, which is probably due to prespore cell division during development21. Percentages of viable spores in chimeric structures were proportional to the percentage of wild type cells in the starting mixture. We developed these spores as clones and confirmed by examination of spores in their fruiting bodies that they all derived from Aa2. Evidently, the *spaA*-mutant has a cell-autonomous defect in spore formation.

Expression of post-aggregative genes in *spaA*-. The homology of SpaA with the transcription factor CudA suggests that SpaA is also a transcription factor. We therefore compared developmental expression of the prespore genes *pspA*22 and cotC21, the gene spore gene *spaA*24 and the prestalk gene *ecmA*25 between wild-type and *spaA*-cells, using quantitative reverse transcription-PCR (qRT-PCR). *Ecma, cotC*, and *pspA* are highly expressed in wild-type slugs at 15 h of development, with expression decreasing during fruiting body formation. Expression of *ecmA* and *pspA* is 30–50% increased in *spaA*-cells, while *cotC* expression is 50% decreased (Fig. 2A). *spaA* is optimally expressed during mid-culmination in wild-type, but not at all in *spaA*-, indicating that SpaA is particularly important for spore gene expression.

Two transcription factors, SrfA and BzpF are required for full spore viability7,8. Transcriptomic analyses identified *sigF* and *spaA* as target genes for SrfA, and *DDB* G0290419 as a target gene for BzpF7,8,26. *BzpF* is upregulated in spores, while *srfA* is expressed in both prestalk and prespore cells, with expression being upregulated in maturing spores. Figure 2B shows that *bzfF* and its target *DDB* G0290419 are still expressed in the *spaA*-, mutant,
Figure 1. Identification of SpaA by REMI mutagenesis and validation by gene knock-out. (A) REMI mutant phenotype. Wild-type Ax2 cells, transformed with cotC-mRFP were subjected to REMI mutagenesis and a clone, b39, with reduced red fluorescence in slugs and fruiting bodies was isolated. Bar: 50 µm. (B) Individual cells. Prespore cells and spores harvested from Ax2 and b39 slugs and fruiting bodies, respectively, were photographed under epifluorescence with longer exposure for the b39 clone. Bar: 3 µm. (C) Phylogeny of mutant gene. B39 was defective in a CudA-like nuclear factor, SpaA. SpaA sequence was aligned with all D. discoideum CudA-like proteins (DDB_G prefix), an Entamoeba histolytica CudA (AAC41578) and the closest homologs to SpaA in the Dictyostelids D. purpureum (DPU1258757), D. lacteum (DLA_07383), Polysphondylium pallidum (PPL_00580) and D. fasciculatum (DFA_08790). A well conserved segment of the alignment (AA184-AA589 of SpaA) was subjected to Bayesian phylogenetic inference. The tree is rooted at midpoint and posterior probabilities of the nodes are indicated. Colour coding of species names: red, green, blue violet: major groups 1, 2, 3 and 4 of Dictyostelia, respectively, amber: non-dictyostelid Amoebozoa. (D,E) Recapitulated spaA- mutant. A spaA knock-out was generated by homologous recombination (see Supplementary Fig. S2). Wild type Ax2 and spaA- cells were distributed on non-nutrient agar and photographed after slugs (D) and fruiting bodies (E) had formed. Bar: 100 µm. (F) Spore morphology. Ax2 and spaA- spores were fixed and stained with anti-spore antibodies (left) or Calcofluor (right), and photographed under phase contrast (bottom) or epifluorescence (top). Bar: 5 µm. (G) Sporulation efficiency. Fruiting bodies were developed from 3 × 10^6 cells plated on 1 cm^2 filters. Filters were vortexed with 0.1% Triton-X100 after 21 h when fruiting bodies had formed and at two later time points. After spore counting, the percentage of spores relative to the number of plated cells was calculated. Mean and SD of three independent experiments.
Figure 2. Expression of cell type specific genes in spaA- cells. Wild-type Ax2 and spaA- cells were plated for development to fruiting bodies (24 h), and total RNA was isolated at 2 h intervals, starting at mounds (12 h). mRNA levels for the prespore genes cotC and pspA, the prestalk gene ecmA, the spore gene SpiA, the constitutively expressed gene Ig7 (A) the transcription factors srfA and bzpF and their respective targets sigF and DDB_G0290419 (B) were measured by qRT-PCR. Data are expressed as fraction of the highest expression obtained with Ax2 for each experiment. Because the timing of peak expression differs between experiments, data from three experiments are plotted separately. Black and grey lines connect the mean values of the three experiments for Ax2 and spaA-, respectively.
although expression seems delayed. SrfA is similarly expressed in spaA- and wild-type cells at 12–14 h. However, the transient increase at 18 h of wild-type srfA expression is absent in spaA-. Expression of the SrfA target sigF is lost in spaA-. SpaA appears to be essential for expression of SrfA and SrfA-dependent genes during sporulation, whereas it is not critically required for expression of BzpF and one of its target genes.

**PKA activation does not rescue the sporulation defect of spaA-.** The transition of prespore cells into spores requires PKA\(^{12,27}\) and to assess whether SpaA acts either upstream or downstream of PKA, or in a parallel pathway, we tested whether overexpression of the PKA catalytic subunit (PkaC) could restore sporation formation in spaA-. A construct in which pkaC was fused N-terminally to the act15 promoter and C-terminally to YFP was transformed into wild-type and spaA- cells, and clones with high expression, as evident from Western blots, were selected. Ax2 cells with high expression of A15::pkaC_YFP showed precocious sporulation and mound arrest (Fig. 3A,B), while lower expressing clones arrested as slugs as reported earlier\(^{28}\). SpaA-/A15::pkaC_YFP cells also showed mound arrest, but with no resistant spores were formed (Fig. 3A,B). Transcription of the SpaA-dependent genes spiA and sigF was also not restored (Fig. 3C) and bzpF expression was still delayed in spaA-/A15::pkaC_YFP cells, as was the case in spaA-. (Fig. 2).

To validate that active PKA cannot restore the sporulation defect of spaA-, we acutely activated PKA in early culminant wild-type and spaA- cells with the membrane-permeant PKA activator, 8Br-cAMP. Figure 3D shows that 8Br-cAMP effectively induces spiA and sigF expression in wild-type, but not in spaA-. BzpF induction by 8Br-cAMP is about 40% reduced in spaA-. Complex expression of srfA during development is regulated by alternative promoters that generate mRNAs with different exons in the 5’UTR. The most distal promoter activates srfA expression during sporulation, and its activity is enhanced when 8Br-cAMP is added to the substratum\(^{9,10}\). We found that 8Br-cAMP decreased srfA expression from its full endogenous promoter in both Ax2 and spaA-. The control gene Ig7 was similarly expressed in Ax2 and spaA-, irrespective of treatment with 8Br-cAMP.

**SpaA binds to the spore-specific promoters in a PKA dependent manner.** To investigate whether SpaA binds to spore gene promoters, we performed chromatin immuno-precipitation, using the SpaA_YFP fusion protein expressed from the spaA promoter in spaA- cells (Supplementary Fig. S3C). The construct was expressed under hygromycin selection, which requires only a single copy number of the vector, to minimize artefacts due to overexpression. SpaA-/SpaA_YFP and spaA- control cells were developed to early culminants and incubated for 1 h without and with 8Br-cAMP to enhance expression of spore genes. After protein-DNA crosslinking and DNA shearing, cell lysates were immuno-precipitated with or without GFP antibody, and the presence of target gene promoters in the immuno-precipitate was determined by qPCR. For srfA, PCR primers were designed against promoter sequences essential for spore-specific srfA expression. Figure 4 shows that over 10-fold more cotC, srfA, spiA and sigF promoter sequences were amplified from spaA-/SpaA_YFP preparations incubated with GFP antibodies than without antibody, and that untransformed spaA- cells showed almost no pull-down of promoter sequences. For srfA, spiA and sigF, promoter pull-down was lower at t = 0 h and without 8Br-cAMP treatment, but cotC promoter pull-down was highest at the start of the experiment, in agreement with the earlier developmental expression of cotC (Fig. 2A). qPCR with primers close to the 3’ end of the cotC coding region showed some amplification in the antibody treated spaA-/SpaA_YFP samples, which could result from some large DNA fragments surviving shearing. Overall, the experiment shows that SpaA binds directly to the promoter regions of its target genes, consolidating its role as transcriptional regulator.

**ChIPseq analysis identifies more than hundred SpaA target genes.** We performed ChIPseq to identify all genes that are regulated by SpaA. spaA-/SpaA_YFP cells were developed into culminants. DNA libraries with fragments of ~300 bp were prepared from ChIPed DNA in three separate experiments and subjected to 75 bp paired-end sequencing. After mapping reads to the genome, the read pairs that mapped concordantly were used to identify peaks with read counts that significantly exceeded read counts from control libraries. Such peaks were annotated to the gene with the closest start codon. The three experiments yielded a total of 2036 peaks, of which 815 were shared between experiments 2 and 3 and 345 between all three experiments (Supplementary Table S1). This low overlap is largely due to low ChIP efficiency in the first experiment. The 815 peaks were used to identify peaks with read counts that significantly exceeded read counts from control libraries.

Most of the 216 protein-coding genes, ChIPed by SpaA in all three experiments, showed highest expression in either the slug or fruiting body stage (Fig. 5A), and 58% and 10% were over 2-fold enriched in prespore or prestalk cells, respectively. Not all genes detected in the published time course also showed expression in the cell-type specificity experiment\(^{21}\). The percentage of prespore- or prestalk- enriched genes is therefore calculated from the 202 genes with read counts in the cell-type specificity experiment (Fig. 5C).

The larger set of 364 protein-coding genes, common to experiments 2 and 3, showed similar developmental regulation (Supplementary Fig. S6), but was 9% less enriched in prespore cells (Supplementary Fig. S5). However, since this set had 49 more prespore-specific genes than the 216 set, likely to be valid SpaA targets, it was included in further analysis. The number of prespore-enriched genes common to all three experiments, or experiments 2 and 3 only, are 117 and 166, respectively (Supplementary Fig. S5), which, considering the (pre)spore-specificity of SpaA itself, sets the limits to the number of likely SpaA targets. Cluster analysis based on developmental expression indicated that genes upregulated after 12 h of development showed higher statistical significance of
Figure 3. PkaC overexpression and 8Br-cAMP treatment of spaA-.

(A) Mound arrest. Ax2 and spaA- cells, transformed with an A15::pkaC-YFP construct, were developed for 24 h (when wild-type has formed fruiting bodies, see Fig. 1E) and photographed. Bar: 300 µm.

(B) Spore formation. The efficiency of sporulation of A15::pkaC-YFP transformed AX2 and spaA- cells was measured as described for Fig. 1G.

(C) PkaC effects on gene expression. Cells were developed for 16 h at 12 °C and 1, 3 and 5 h at 22 °C. At 3 and 5 h spores have formed in Ax2/A15::pkaC-YFP. RNA was isolated and transcription of spiA, sigF, bzpF and Ig7 was determined by qRT-PCR. Values are expressed as fraction of the highest expression obtained with Ax2/A15::pkaC-YFP. Results of three individual experiments are shown.

(D) 8Br-cAMP effects on gene expression. Ax2 and spaA- early culminants were dissociated, resuspended to 10^7 cells/ml and incubated with or without 15 mM 8Br-cAMP. RNAs were isolated at t0 and after 2 h of incubation, and levels of spiA, sigF, bzpF, srfA, and control Ig7 transcripts were determined by qRT-PCR. Data are expressed as fraction of the highest expression obtained with Ax2, and means and SD of 3 experiments are shown. Significant differences between some treatments as determined by a rank sum test are indicated (*P < 0.01; -: P ≥ 0.05).
read peaks (lower q-values) and more pronounced prespore enrichment than clusters that were expressed earlier or constitutively, or that were downregulated in development (see supplementary spreadsheet SupData1, sheets 3 and 4). Since SpaA is itself only expressed after aggregation, this suggests that the early expressed and down-regulated genes bind SpaA fortuitously.

Figure 4. Chromatin immuno-precipitation with SpaA-YFP. SpaA- and spaA-/SpaA-YFP early culminants were dissociated and incubated for 1 h with or without 10 mM 8Br-cAMP. After crosslinking to protein, chromatin was sheared and immuno-precipitated with or without α-GFP antibody. The presence of cotC, srfA, spiA and sigF promoter sequences in the immuno-precipitates was determined by qPCR using promoter specific primers (Supplementary Table S2), or cotC coding sequence (CDS) specific primers as control. Amounts of amplified products are normalized to amounts obtained from diluted total cell lysate and expressed as fraction of DNA amplified from promoter regions at 0 h in antibody treated SpaA-YFP expressing cells. Means and SD of 3 experiments. Significant changes (P < 0.05) between some treatments are indicated by asterisks.
Gene ontology (GO) analysis revealed that both the 216 and 364 sets of SpaA targets show in the category Biological Process strongest overrepresentation of GO terms associated with “sporulation”, “cell wall assembly” and “fruiting body development”, while in the category Cellular Component GO terms associated with the plasma membrane and spore wall are most overrepresented (SupData1, sheets 5 and 6). Among the SpaA target genes with known or predicted functions are many spore coat genes (cotA-C, pspB, D, psvA, DDB_G0291392), an expansin, expl3, the poly-glycosyltransferase pgtB29, the UDP-glucose 4-epimerase galE30, the GlcNAc transferase gnt11 and the cellulose synthase, dcsA31, all involved in spore wall synthesis, and the water channels aqpA32 and wacA33 (Table 1 and SupData1, sheet 7). Ten SpaA target genes are transcription factors of which three spaA, cudA34 and srfA34 are involved in sporulation, while loss of stkA causes prespore cells to transdifferentiate into stalk cells11.

Validation of SpaA targets and cross-regulation of other transcription factors. To validate the ChIPseq approach, the promoter pulldown of 6 putative SpaA targets in SpaA-ChIPed chromatin was tested by qPCR. Figure 6A shows that all 6 promoters were amplified. As expected for SpaA targets, CotC and sigF are underexpressed in spaA- (Fig. 2) and we investigated this also for stkA and 5 other putative targets. The prespore genes, aqpA and DDB_G0280215, expressed after 16 h, are also down-regulated, but cudA and stkA which are less prespore-enriched and transcribed earlier, are still expressed in spaA- (Fig. 6B). Expression of prestalk genes DDB_G0284619 and DDB_G0277581 are not significantly altered or delayed in spaA-, respectively. Apparently, late expressed prespore genes are more stringently regulated by SpaA than early expressed or non-prespore genes.

We further assessed whether SpaA shares targets with other transcription factors that promote sporulation. For SrfA 41 putative targets were detected by interrogation of microarrays36. BzpF has 24 putative and 15 confirmed targets and for stkA 8 targets were identified by differential display40. CudA has only 2 confirmed targets, cotC34 and the prestalk gene expl7. SpaA shares no targets with BzpF, and only 5 targets with SrfA, amongst which sigF and spaA (Table 2). There were 2 and 1 SpaA targets in common with StkA and CudA, respectively, but these numbers may be underestimates, due to the low number of identified targets for either stkA or CudA. Because SrfA is down-regulated in spaA- cells (Fig. 2B), SpaA affects SrfA targets mostly by inducing expression of SrfA itself. This is not the case for CudA and StkA, which are still expressed in spaA- (Fig. 6B). We also investigated spaA expression in cudA- and srfA- mutants (the stkA- mutant is not available anymore). However, it appeared that neither CudA nor SrfA are required for SpaA expression (Fig. 6D).
| spore wall/ membrane | transcription factor | protein kinase/ phosphatase | various signalling genes |
|----------------------|----------------------|----------------------------|-------------------------|
| supA                 | bpyA                 | abcD2                      | NTF                     |
| cotA                 | cudA                 | DDB_G0267686               | psvC                    |
| cotB                 | DDB_G0287317         | DDB_G0268841               |                         |
| cotC                 | DDB_G0293478         | glkA                       | abcG6                   |
| dcsA                 | dimB                 | lkb1                       | acadH, pdbH             |
| DDB_G0291392         | gtlA                 | pakG                       | arfA, secG              |
| expl3                | gtaP                 | pxi                        | arpB, tagB              |
| gatE                 | mybE                 | amg1                       | cuaA, yeaA              |
| gnt1                 | mykN                 | darA                       |                         |
| gntB                 | gpaA                 | protein phosphatase DDB_G0269128 |
| gntR                 | srfA                 | DDB_G0272727               |                         |
| gntD                 | stkA                 | DDB_G0271350               | DDB_G0282093            |
| gntE                 | pipC                 | DDB_G0284619               |                         |
| gatG                 | dntA                 |                            |                         |
| gatA                 | gpaA                 |                            |                         |
| watA                 | gplD                 |                            |                         |

Table 1. Spore physiology- and signalling genes that bind to SpaA. Data are summarized from a listing complete with peak enrichment and q-values of the 364 SpaA target genes common to ChIPseq experiments 2 and 3 (see supplementary spreadsheet SupData1, sheet 7) Underlined: enriched in prespore cells; italics: null mutant has sporulation defect.

Discussion

A sporulation deficient mutant was isolated from a REMI screen for mutants defective in prespore gene expression. The mutant partially excytosed its prespore vesicles, but was incapable of synthesizing the spore wall and its mutated gene, spaA, encoded a deeply conserved cudA-type transcription factor. Similar to abcA-, actA-, and psA:PKARm mutants that cannot activate PKA in prespore cells2,12, spaA- mutants leave prespore cells amoeboid in the spore head, suggesting that SpaA acts downstream of PKA. This was validated by observations that SpaA binds to spore promoters in a PKA-dependent manner and that spaA- mutants lack PKA-induced spore gene expression. Using purified TAP-tagged SpaA and YFP-tagged PKA-C, we were however unable to detect direct phosphorylation of SpaA by PKA (unpublished results), indicating that there must be at least one phosphorylated intermediate.

High throughput sequencing of DNA immunoprecipitated by SpaA-YFP detected 216 to 364 protein coding genes with significant binding to SpaA in their 5′ intergenic region. The gene set contained many spore coat genes and was enriched in gene ontology terms associated with sporulation, spore wall assembly and fruiting body development. About half of the genes were upregulated in the slug and fruiting body stage and showed highest expression in prespore cells. Genes with earlier expression and/or lacking prespore specificity were not or less stringently down-regulated in the spaA- mutant (Fig. 6B,C), suggesting that the affinity of their promoters for SpaA was fortuitous or less relevant for their overall regulation.

Among the SpaA target genes was the transcription factor srfA, which also regulates spore gene expression. Five out of the 41 SrfA target genes were also SpaA targets, while SpaA is not itself an SrfA target. This indicates that besides the more than 100 spore genes that are directly activated by SpaA, SpaA controls even more genes by inducing SrfA expression. This places SpaA at the top of a hierarchy that controls spore differentiation (Fig. 7). CudA and StkA, two other transcription factors that are involved in spore differentiation44, as well as MybE and DimB with roles in prestalk differentiation41 are also putative targets for SpaA (Table 1). However, there are up till now only a few target genes known for either of these factors, making it difficult to assess to what extent they contribute to the genes that are ultimately regulated by SpaA. BzpF, also required for sporulation, and its target genes do not require SpaA for expression. However, whereas spaA- makes no walled spores, bzpF- makes spores with cellulose-rich walls, which disintegrate after a few days7. This suggests that BzpF acts later by activating genes required for dormancy.

Many SpaA target genes encode proteins with different roles in assembly of the spore coat42, which were shown to be coordinately regulated by PKA activation43. Overall, the pronounced effects of spaA deletion on sporulation and the vast number of genes under SpaA control hallmark this transcription factor as the key regulator of Dictyostelium sporulation.

Methods

Cell culture. Dictyostelium discoideum Ax2 was cultured either in HL5 axenic medium (Formedium, UK) or on SM agar plates in association with Klebsiella aerogenes. For development, cells were distributed at 3 × 10^6 cells/cm^2 on non-nutrient agar, or on nitrocellulose filters supported by filter pads soaked with DB (1 mM CaCl_2 and 2 mM MgCl_2 in 5 mM Na/K phosphate buffer, pH 6.5).

REMI mutagenesis of cotC-mRFP transformed cells. The cotC gene, ranging from nt −743 relative to the start codon to the end of the coding sequence was amplified from Ax2 genomic DNA using primers cotC-f and cotC-r (Supplementary Table S2) and blunt-end cloned into vector pJet1.2 (Thermo Fisher Scientific,
Whaltham, MA). The cotC fragment was excised with XbaI and BamHI and cloned into the XbaI/BamHI digested plasmid pExp4/ecmO:mRFPmars, replacing the ecmO promoter. The resulting cotC-mRFP gene fusion was cloned into pExpHyg, a pExp-4(+) vector, in which the neomycin resistance cassette was replaced by the

**Table 2.** Target overlap between SpaA and other transcription factors. The identity of the shared target genes is listed in Supdata1, sheet 8. (*1*) number of genes annotated to peaks observed in all 3 experiments. (*2*) number of genes annotated to peaks common to experiments 2 and 3.

| Known downstream genes | SpaA targets |
|------------------------|--------------|
|                        | Common to exp. 1-3*1 | Common to exp. 2 & 3*2 |
| SpaA                   | 216          | 364              |
| SrfA                   | 41           | 2                | 5               |
| StkA                   | 8            | 1                | 2               |
| BzpF                   | 24           | 0                | 0               |
| CudA                   | 2            | 1                | 1               |
Figure 7. Hierarchy of transcription factors that regulate *Dictyostelium* sporulation. SrfA upregulates 41 genes required for spore viability and elliptical spore shape, and is itself upregulated by SpaA, which controls >100 spore genes, amongst which 5 are co-regulated with SrfA. BzpF upregulates 15–24 genes that act to prevent precocious germination. All three transcription factors act downstream of PKA.

hygromycin resistance cassette from pHygTm(+)/pG7 using XbaI and Xhol. The construct was transformed into Ax2 cells and transformants were selected at 30 µg/ml hygromycin.

For REMI mutagenesis a clonal isolate of AX2/cotC-mRFP was transformed with pUCBsrΔBam, linearized with BamiII, and 1 unit of DpnII13. Transformants were selected at 10 µg/ml blasticidin and clonally plated with *K. aerogenes*. Developing clones were inspected under a stereo microscope and a compound fluorescence microscope for defects in slug and fruiting body morphology and/or defects in red fluorescent staining of the prespore and spore regions.

The site of plasmid insertion in selected mutants was determined by inverse PCR45 using primers Remi-f and Remi-r (Supplementary Table S2). The amplified fragment was sequenced with primer BsrA15r (Supplementary Table S2).

**Recapitulation of the spaA lesion by gene knock-out.** To generate an *spaA* knock-out vector, a genomic fragment of the *spaA* coding region was amplified with primers spaA-f1 and spaA-r1 (Supplementary Table S2) and cloned into vector pJet1.2. The *spaA* region, located 5’ to the internal BamHI site at nucleotide 1155, was replaced with a fragment amplified with spaA-f1 and spaA963r (Supplementary Table S2), deleting a region between 964 and 1155, while maintaining the BamHI site. The blasticidin resistance cassette of pLPBLP46 was excised with Smal and blunt-end ligated into the BamHI digested and filled-in *spaA*-KO vector. The vector was linearised with EcoRI and transformed into Ax2 cells. Transformants were selected at 10 µg/ml blasticidin and diagnosed for *spaA* gene disruption by two PCR reactions (Supplementary Fig. S2).

A *D. discoideum* genomic fragment, containing the *spaA* coding region and 2.6 kb upstream of the start codon, was amplified with primers spaA-f2 and spaA-r2 (Supplementary Table S2), digested with Sall and EcoRI and cloned into vector pExp4. YFP was next inserted at the 3’ end of *spaA* using EcoRI and Xhol. The *spaA*-YFP fragment was excised using Sall and Xhol and ligated into Sall/Xhol digested pExpHyg. The construct was transformed into Ax2 and *spaA*- cells, and transformants were selected at 30 µg/ml hygromycin. For Western analysis, slug stage cells were lysed in SDS-sample buffer, proteins were separated on 4–12% polyacrylamide gels (Thermo Fisher Scientific, Whaltham, MA), transferred to nitrocellulose and probed with anti-GFP antibody (Roche Applied Science, Penzberg, Germany), followed by HRP-conjugated anti-mouse antibody. YFP-positive bands were detected using SuperSignal West Pico Chemiluminescent Substrate (Thermo Fisher Scientific, Whaltham, MA).

**Immunostaining.** Spores were fixed in 85% methanol and incubated with rabbit-anti-spore antibodies47, diluted 1:10,000 in PBS with 5% bovine serum albumin (BSA) and with 1:2000 diluted Alexa-488 conjugated goat-anti-rabbit-IgG (Thermo Fisher Scientific, Whaltham, MA). Cellulose was stained with 20 µg/ml Calcofluor White (Sigma-Aldrich, St. Louis, MO). For whole mount staining, structures developed on polytetrafluoroethylene membrane (Merck Millipore, Billerica, MA), were fixed with 50% and 100% methanol, successively, and stained with 1:2000 diluted mouse-anti-GFP antibody and 1:2000 diluted Alexa-Fluor594 conjugated anti-mouse antibody (Thermo Fisher Scientific, Whaltham, MA). Structures were mounted in the presence of 3 µM DAPI and imaged using a Leica LP2 confocal microscope.

**RNA analysis by qRT-PCR.** RNA was isolated from about 10^7 cells using the RNAeasy mini kit (Qiagen, Hilden, Germany) and transcribed into cDNA with the ImProm-II Reverse Transcription System (Promega, Fitchburg, WI) or the sensiFAST cDNA synthesis kit (Bioline, London, UK) in the experiments of Fig. 2 or Fig. 6, respectively. Quantitative PCR (qPCR) was performed using PerfeCTa SYBR Green SuperMix (Quanta biosciences, Beverly, MA) with technical duplicates and the primers listed in Supplementary Table S2.

**Chromatin immunoprecipitation (ChIP).** Cells, developed into early culminants, were incubated with and without 10 nM 8Br-cAMP for 1 hr. Cells were fixed with 1% formaldehyde in PBS at a density of 5 × 10^7 cells/ml for 10 min, and for another 15 min after addition of glycine to a final concentration of 125 mM. Cells were washed with PBS, followed by RET buffer (50 mM TRIS, pH 8.0, 150 mM NaCl, 0.1% (w/v) SDS, 1% (v/v) NP-40, 0.5% (w/v) sodium deoxycholate, 2 mM EDTA, 0.05% (v/v) Triton X-100 in 50 mM Tris, pH 8), and resuspended in RET buffer containing Complete EDTA-free protease inhibitor cocktail (Roche Applied Science, Penzberg, Germany). Chromatin was sheared by sonication (Branson Sonifier 150) with 3 pulses of 30 s at setting 6 to produce fragments of 100 to 1000 bp. The lysate was centrifuged at 16000 × g for 10 min, and 30 µl of the supernatant was kept as total DNA. For immunoprecipitation, 350 µl supernatant was incubated overnight at 4°C with anti-GFP antibody and ProteinG-Dynabeads (Thermo Fisher Scientific, Whaltham, MA). Beads were washed sequentially with RET buffer, TTST buffer (150 mM NaCl, 1% Triton X100, 0.1% SDS, 2 mM EDTA, 0.5 M Tris, pH 8) and then with buffer containing 0.1% SDS, 1% Triton X100, 0.1% sodium dodecyl sulfate and 1 mg/ml Proteinase K (Roche Applied Science, Penzberg, Germany).
0.05% Tween20 in 50 mM Tris-Cl, pH 8) and LiCl buffer (250 mM LiCl, 1% sodium deoxycholate, 1% NP40, 1 mM EDTA in 10 mM Tris, pH 8), and eluted with 1% SDS and 1 mM EDTA in 50 mM Tris-Cl, pH 7.5. The eluate and the total DNA was supplemented with 1/10 volume of 3 M NaCl and incubated at 65 °C overnight to reverse the cross-link. The cross-linked DNA was treated with 100 μg/ml proteinase K and 100 ng/ml RNase, and purified on a QIAquick column (Qiagen, Hilden, Germany). The amount of immuno-precipitated DNA was determined by qPCR using the primers listed in Supplementary Table S2 and PerfeCTa SYBR Green SuperMix with technical duplicates. Total DNA was 50x diluted before qPCR to obtain a similar amplification rates as ChIP DNA. In cases where DNA fragments were undetectable and failed to get valid Ct values, the amount was assumed to be zero.

**ChIP-seq.** ChIP was performed as described above, using a spak-/spaA-YFP mixture of slugs to late culminants, except that samples were sonicated 5 × 30 s at setting 8 to obtain smaller fragments. 20 μl lysate was kept as total DNA, and immunoprecipitation was performed with anti-GFP antibody on 1.1 ml lysate. Control precipitation without antibody was performed from 350 μl lysate. Aliquots of total chromatin and immunoprecipitates were used to analyse the presence of promoter sequences by qPCR (Fig. 6), with the amount of amplified product in immuno-precipitates adjusted by sample volume and expressed as relative amount to 30x diluted total DNA. Sequencing libraries were constructed from ChIPed DNA and 30x diluted total DNA as follows: DNA ends were repaired with Klenow polymerase and phosphorylated with T4 polynucleotide kinase. After addition of an A-overhang, pre-annealed ChIP-seq Top and Bottom adaptors (Supplementary Table S3) were ligation onto the DNAs. Between steps, DNA was purified with Agencourt AMPure XP beads (Beckman Coulter, Brea, CA). DNA was amplified with the forward and reverse ChIPseq primers (Supplementary Table S3) and fragments <800 bp were isolated by gel electrophoresis. Each sample library was verified by Qubit 3.0 and Agilent 2200 TapeStation before pooling. Libraries were pooled to allow 6 samples per run on the NextSeq500 platform. Paired-end Illumina sequencing was performed using the Mid-Output v2, 150 cycle kit. Sequence reads were mapped against the *D. discoideum* genome (v.13–05–2009) using Bowtie2.48 Reads mapped concordantly within 700 bp were used to call peaks by MACS2 with a q-value cut off of <0.01, allowing a 200 bp shift in positions of peak summits between experiments. Peaks were annotated to the gene with the closest start codon, using ChIPpeakAnno. Gene ontology (GO) enrichment was determined using the Amigo tool at the GO consortium (www.geneontology.org/) with a threshold cutoff of p ≤ 0.05.

**Data availability.** ChIPseq data have been deposited in the ArrayExpress database at EMBL-EBI (www.ebi.ac.uk/arrayexpress) under accession number E-MTAB-6000. All knockout mutants and plasmid constructs have been deposited at the Dictyostelium Stock Center http://dictybase.org/StockCenter/StockCenter.html.

**References**

1. Schap, P. Evolution of developmental signalling in Dictyostelid social amoebas. *Curr Opin Genet Dev* **39**, 29–34 (2016).
2. Loomis, W. F. Cell signaling during development of Dictyostelium. *Dev Biol* **391**, 1–16 (2014).
3. Du, Q. et al. The cyclic AMP phosphodiesterase RegA critically regulates encystation in social and pathogenic amoebas. *Cellular Signalling* **26**, 453–459 (2014).
4. Kawabe, Y., Schüde, C., Du, Q. & Schap, P. A conserved signalling pathway for amoeboid encystation that was co-opted for multicellular development. *Scientific reports* **5**, 9644 (2015).
5. Schaap, P. et al. The Physarum polycephalum Genome Reveals Extensive Use of Prokaryotic Two-Component and Metazoan-Type Tyrosine Kinase Signalling. *Genome Biol Evol* **8**, 109–125 (2015).
6. Fukuzawa, M., Hopper, N. & Williams, J. cadA: a Dictyostelium gene with pleiotropic effects on cellular differentiation and slug behaviour. *Development* **124**, 2719–2728 (1997).
7. Huang, E. et al. RbpX is a CREB-like transcription factor that regulates spore maturation and stability in Dictyostelium. *Developmental Biology** **358**, 137–146 (2011).
8. Escalante, R. & Sastre, L. A serum response factor homolog is required for spore differentiation in Dictyostelium. *Development** **125**, 3801–3808 (1998).
9. Escalante, R., Vicente, J. J., Moreno, N. & Sastre, L. The MADS-box gene srfA is expressed in a complex pattern under the control of alternative promoters and is essential for different aspects of Dictyostelium development. *Dev Biol* **235**, 314–329 (2001).
10. Escalante, R. & Sastre, L. Regulated expression of the MADS-box transcription factor SrfA mediates activation of gene expression by protein kinase A during Dictyostelium spore formation. *Mech Dev* **117**, 201–208 (2002).
11. Chang, W.-T., Newell, P. C. & Gross, J. D. Identification of the cell fate gene Stalky in Dictyostelium. *Cell** **87**, 471–481 (1996).
12. Hopper, N. A., Harwood, A. J., Bouzid, S., Veron, M. & Williams, J. G. Activation of the prespore and spore cell pathway of Dictyostelium differentiation by CAMP-dependent protein kinase and evidence for its upstream regulation by ammonia. *EMBO J* **12**, 2459–2466 (1993).
13. Kuspa, A. & Loomis, W. F. Tagging developmental genes in Dictyostelium by restriction enzyme-mediated integration of plasmidDNA. *Proc Natl Acad Sci USA* **89**, 8803–8807 (1992).
14. Müller-Täubchenberger, A. et al. Monomeric red fluorescent protein variants used for imaging studies in different species. *Eur J Cell Biol* **85**, 1119–1129 (2006).
15. Fosnaugh, K. L. & Loomis, W. F. Spore coat genes SP60 and SP70 of Dictyostelium discoideum. *Mol Cell Biol* **9**, 5215–5218 (1989).
16. Yamada, Y., Wang, H. Y., Fukuzawa, M., Barton, G. J. & Williams, J. G. A new family of transcription factors. *Development* **135**, 3093–3101 (2008).
17. Suguang, R. et al. Comparative genomics of the social amoebae Dictyostelium discoideum and Dictyostelium purpureum. *Genome Biol* **2**, R20 (2011).
18. Beaudouin, M. et al. Comparative genomics of the social amoebae Dictyostelium discoideum and Dictyostelium purpureum. *Genome Biol* **2**, R20 (2011).
19. Heidel, A. et al. Phylogeny-wide analysis of social amoeba genomes highlights ancient origins for complex intercellular communication. *Genome Res* **18**, 1882–1891 (2011).
20. Glöckner, G. et al. The multicellularities of dictyostelid social amoebas. *Nature communications* **7**, 12085 (2016).
21. Takeuchi, I. Immunohistochemical and immunohistochemical studies on the development of the cellular slime mold *Dictyostelium mucoroides*. *Dev Biol* **8**, 1–26 (1965).
22. Parikh, A. et al. Conserved developmental transcription factors in evolutionarily divergent species. *Genome Biol* **11**, R35 (2010).
23. Zimmerman, W. & Weijer, C. J. Analysis of cell cycle progression during the development of Dictyostelium and its relationship to differentiation. *Dev Biol* **160**, 176–185 (1993).
24. Early, A. E. et al. Structural characterization of Dictyostelium discoideum prespore-specific gene D19 and of its product, cell surface glycoprotein pSA. *Mol Cell Biol* **8**, 3458–3466 (1988).
Acknowledgements

We thank Dr. Nicola Wiechen and Dr. Tom Owen-Hughes for ChIP-seq oligonucleotide primers and guidance with ChIPseq library preparation. We are grateful to Dr. Christian Cole for advice on ChIP-seq experimental design and to Dr. Reema Singh for initial computation. We thank Prof. Jeff Williams for plasmids pExp4/ecmO:mRFPmars and pHygTm(+)/+pG7. The project was funded by Wellcome Trust grant 100293/Z/12/Z.

Author Contributions

Y.Y. and P.S. conceptualized the study. Y.Y. performed most experiments and bioinformatic analysis, A.C. performed ChIPseq library preparation and sequencing and Y.Y. and P.S. wrote the manuscript.

Additional Information

Supplementary information accompanies this paper at https://doi.org/10.1038/s41598-018-24915-w.

Competing Interests: The authors declare no competing interests.

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s) 2018