Photoperiodic control of sugar release during the floral transition: What is the role of sugars in the florigenic signal?

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Florigen is a mobile signal released by the leaves that reaching the shoot apical meristem (SAM), changes its developmental program from vegetative to reproductive. The protein FLOWERING LOCUS T (FT) constitutes an important element of the florigen, but other components such as sugars, have been also proposed to be part of this signal.1-5 We have studied the accumulation and composition of starch during the floral transition in Arabidopsis thaliana in order to understand the role of carbon mobilization in this process. In A. thaliana and Antirrhinum majus the gene coding for the Granule-Bound Starch Synthase (GBSS) is regulated by the circadian clock6,7 while in the green alga Chlamydomonas reinhardtii the homolog gene CrGBSS is controlled by photoperiod and circadian signals.8,9 In a recent paper10 we described the role of the central photoperiodic factor CONSTANS (CO) in the regulation of GBSS expression in Arabidopsis. This regulation is in the basis of the change in the balance between starch and free sugars observed during the floral transition. We propose that this regulation may contribute to the florigenic signal and to the increase in sugar transport required during the flowering process.

Introduction

Plant life cycle is influenced by environmental conditions that affect their ability to obtain energy for its correct growth and development.11 The floral transition is a crucial decision in the life cycle of a plant, so that failing to trigger the reproductive signal at the right time of the year, has a serious impact on the ability to produce offspring. For this reason, the process is tightly regulated12 and plants have solved the problem by synchronizing their life cycle to the changing seasons. This timing is particularly important in intermediate latitudes where changes in environmental conditions are marked and predictable throughout the year. The photoperiod pathway controls the floral transition in response to day length in Arabidopsis thaliana and CO is a central gene in this process.13 The involvement of CO in regulating the photoperiod response is evolutionarily conserved.8,14 Thus, GrCO, a CO ortholog, controls the photoperiodic response in the green alga C. reinhardtii and directly affects starch metabolism through the transcriptional control of the algal ortholog of the GBSS gene.9 Starch is the most important form of carbon reserve in plants. The starch granule contains 2 types of polymer, branched amylopectin, synthesized by Soluble Starch Synthases (SSS) and Starch Branching Enzyme (SBE); and linear amylose synthesized exclusively by GBSS.15 Here we have focused our studies on transitory starch in Arabidopsis that is synthesized during the day and partially degraded during the night.16

We have recently described that the same photoperiodic signal that activates the expression of FT through CO is also responsible for the mobilization of sugars during the floral transition.10 This action is mediated by GBSS. GBSS therefore, has a great influence on the composition of starch granule and its structure, in addition to the ability of plants to accumulate and mobilize sugars from it.15 Therefore, the regulation and modification of GBSS expression levels could have an effect on the composition of the starch granule and the floral transition. In this paper we will further discuss the role of the photoperiodic signaling in the control of sugar release in Arabidopsis through the conserved control of GBSS expression and the significance of the sugar burst during the induction of flowering.

Results and Discussion

Starch and free sugar accumulation depends on the length of the day

We have described a mechanism involved in starch mobilization mediated by photoperiodic signals in long day (LD: 16h light/8h dark) in different Arabidopsis wild type ecotypes.10 We...
now show that starch and sugar content are particularly modified in mutant lines of the photoperiodic pathway (Fig. 1).\textsuperscript{17} In \textit{Ler} ecotype background (Fig. 1A) starch accumulation was significantly reduced after flowering (AF) in all photoperiodic mutant lines analyzed. The proportion in starch level reduction AF in \textit{gi-3} was lower compared to other photoperiod mutants, which may be due to the fact that \textit{gi-3} mutant also shows higher levels of starch before flowering (BF). This may be related to the fact that \textit{GIGANTEA} (\textit{GI}) is also involved in regulating carbohydrate accumulation through the circadian clock.\textsuperscript{18-20} Interestingly, all photoperiod mutants analyzed in \textit{Col-0} background (Fig. 1B) showed a significant reduction in starch accumulation both BF and AF compared to wild type plants. This may reflect differences in the photoperiod response in relation to sugar mobilization between both ecotypes.

We also analyzed free sugar levels in \textit{Ler} and \textit{Col-0} mutants of the photoperiod pathway BF and AF (Fig. 1C and D). Mutants of both ecotypes showed some differences related to WT plants, but they were less obvious than differences in starch levels. As with starch accumulation, photoperiod mutants in \textit{Ler} and \textit{Col-0} backgrounds exhibited a differential free sugar accumulation pattern. Again, this was particularly true for \textit{gi} mutants that showed very high levels of free sugars AF in both ecotypes. It should be noted that these measurements were performed at ZT16, time that corresponds to the maximum level of starch accumulation, while we had demonstrated that the most marked differences in sugar levels take place at ZT8.\textsuperscript{10} Nevertheless, this analysis indicates that during the floral transition a difference in the accumulation of free sugars takes place and that it may also change depending on the photoperiod. Since mutant plants in the photoperiod pathway genes are particularly affected in their ability to accumulate starch and free sugars during the floral transition, the day length signals must have an important role in this accumulation.

**Figure 1.** Starch and whole sugar content in \textit{Col-0} and \textit{Ler} mutants BF and AF. (A) Starch content in \textit{Ler} plants and mutant lines \textit{soc1-1, ft-7, co-2} and \textit{gi-3}. (B) Starch content in \textit{Col-0} plants and mutant lines \textit{soc1-2, ft-10, co-10} and \textit{gi-2}. (C) Level of main soluble sugars (glucose, fructose and sucrose) in the same plants as in A. (D) Level of main soluble sugars (glucose, fructose and sucrose) in the same plants as in B. Samples were collected in LD at the end of the day period before (black, BF) and after (gray, AF) flowering. Data represent the means of 3 biological replicates ± s.e.m. Significant differences (Student t-test) between WT BF and AF are marked by asterisk *\(P < 0.01\) and **\(P < 0.001\).

Amylose levels are directly related with flowering time

Transitory starch synthesis and degradation, as well as \textit{GBSS} mRNA levels, are under circadian regulation both in higher plants and algae.\textsuperscript{6,21-22} We have also shown that starch accumulation, amylose synthesis and endogenous levels of sugars in \textit{Arabidopsis} leaves vary drastically before and after the floral transition.\textsuperscript{10} The mobilization of sugars from amylose allows plants to carry out successfully the transition from vegetative to reproductive state. In this sense, it was interesting to study plants with abnormal internal sugar levels in order to confirm this hypothesis.

For this reason we isolated T-DNA insertion mutants in the \textit{GBSS} gene in \textit{Arabidopsis} and studied their capacity to accumulate starch and sugars.\textsuperscript{10} \textit{gbs} mutants were unable to synthesize amylose and accumulated lower levels of sugars during the daytime. In addition, they exhibited a significant delay in flowering time. The linear composition of amylose may constitute an effective carbohydrate reserve that could be readily used to augment the levels of cellular free sugars during the floral transition. In this way, the lack of amylose would alter the capacity to release sugars and would thus produce a delay in the floral transition. We have observed this behavior in our studies on \textit{gbs} mutants and other mutants related with starch composition and storage.

A similar flowering phenotype is observed in mutants affected in starch metabolism such as \textit{aps1} (a starchless mutant)\textsuperscript{23} and...
sex1 (unable to degrade starch). Both present a late flowering phenotype in LD. sex1 mutant showed continuous high levels of starch during 24 h cycles and levels of free sugars were constantly lower than wild type plants over time. On the other hand, aps1 mutant showed the opposite effect, it did not present detectable levels of starch and sugars were constantly higher than in Col-0 plants. Previous results also showed that sex1 contained high levels of amylase, so the low levels of free sugars observed in this mutant suggests that sex1 is unable to mobilize sugars from this polymer during the transition to flowering. In summary, all mutants affected in starch metabolism studied (gbs, aps1 and sex1) shared a common characteristic: they were unable to mobilize sugars from amylase. These results suggest that amylase is essential for the release of sugars during the floral transition. Consequently, a change in amylase accumulation is traduced into changes in flowering time.

**CO induces GBSS expression in a photoperiod-dependent manner**

The flowering delay in LD of the gbs mutants and its day length-dependent expression, suggested that the photoperiodic pathway could be controlling GBSS transcription and that CO could be involved in this process. Further confirmation came from the effect of CO mutation and overexpression on GBSS expression, so that co-10 mutant showed a specific decrease in GBSS expression in the morning, while 35S:CO plants showed a marked increase of GBSS mRNA levels in the morning and a new expression peak in the evening. GBSS expression pattern in short day (SD: 8h light/16h dark) did not show any modification in CO mutant and overexpressor lines and no delay in flowering time in SD of these lines was observed. As CO is not active in SD, this is precisely what was expected from a true CO target. In fact, using ChiP experiments, we also demonstrated that CO could bind directly to GBSS promoter in similar binding sites than those described for the FT promoter and this binding differed BF and AF.

We have here confirmed that GBSS acts through CO by crossing gbs mutant into 35S:CO plants. The inclusion of gbs mutation in the overexpressing background delayed flowering time (Fig. 2A). We further demonstrate that this delay in flowering time is due to a reduced FT expression (Fig. 2B). Thus, CO capacity to alter FT expression is reduced in an amylase-free plant with reduced capacity to mobilize sugars during the floral transition.

Nevertheless, the delay in flowering time observed in the co-10 gbs-1 double mutant in LD (Fig. 2A) indicates that in a very late flowering plant, GBSS must have a developmental role independently of CO. In fact, a double gi-2 gbs-1 mutant plant also flowered later than any of the progenitors (data not shown).

**GBSS fusion to GFP reports starch presence in diverse locations and developmental stages**

We have produced plants that express a translational fusion of GFP to the carboxyl part of GBSS driven by 1 kb from the GBSS promoter (pGBSS:GBSS:GFP). Different tissue samples from recombinant Arabidopsis plants have been observed in diverse developmental stages under the confocal microscope (Fig. 3). GFP was detected in chloroplasts from all green tissues, but in some cases we noticed that GBSS presence, and thus starch accumulation, was present at a different developmental stage than previously suggested.

Developing seeds showed a clear GBSS:GFP signal (Fig. 3A–C). In early silique developmental stages, GFP signal was uniformly distributed in the seed (Fig. 3A and B), whereas in later developmental stages, GBSS was restricted to the outer seed region that can be attributed to the aleurone cell layer. In these mature seeds, although most of carbohydrates have been already converted into reserve fatty acids, the aleurone cell layer remains clearly visible. This suggests that the presence of starch in Arabidopsis seeds, probably feeding sugars to the developed
embryo, remains active longer than previously reported.\(^{26}\) It will be of interest to determine whether this accumulated starch in mature seeds has a significant role during germination.

In the root meristem, GBSS was detected in the columella cell layers where starch accumulates conferring, among other physiological functions, a gravitropic response to the growing root. We have further detected GBSS:GFP fusion in the growing lateral roots, accounting for the observed gravitropic response of these lateral organs (Fig. 3D and F).\(^{27}\) As expected, we could not detect GFP presence in root hairs (Fig 3G). Thus, GBSS and starch seem to be restricted to root organs responding to gravity, although their involvement in other physiological processes can not be ruled out.

Conclusions. Florigen is a complex signal probably composed of several different elements and, although mainly of a photoperiodic nature, may also be influenced by other environmental cues. Sugars are not only a source for structural and energetic physiological processes, but can also have an important signaling role.\(^{1,5}\) Here, we describe how the same mechanism that controls the production of FT is also used by the plant to alter starch composition in order to facilitate a coordinated release of sugars. A possible physiological function for the increase in sugar levels exactly during the floral transition may be related to a role as osmotic pull for the florigen transport through the phloem. Nevertheless, our studies cannot rule out the possibility that this sugar burst during the floral transition could also be used as a reinforcement signal to that triggered by FT or that it constitutes \textit{per se} an independent sugar-based signal that is part of the florigen. Therefore, we conclude that the effect of CO on GBSS could be one of the mechanisms involved in coordinating the induction of flowering by photoperiod and carbon mobilization. Further studies on the nature of these signals and the role in activating downstream genes involved in the floral meristem identity will be needed to support these hypotheses.

**Methods**

**Plant Material and Growth Conditions**

Plants were grown in controlled cabinets on peat-based compost under long day conditions (LD: 16h light/8h dark) as described in Ortiz-Marchena et al.\(^ {10}\) Leaf samples were taken 2 d before and after flowering induction. \textit{Arabidopsis thaliana} plants including wild type Col-0 and Ler, gbs-1, gbs-2, 35S:CO x gbs-1 and 35S:CO x gbs-2 have been described in Ortiz-Marchena et al.\(^ {10}\) The \textit{apsl} mutant was reported by Ventriglia et al.\(^ {23}\) The \textit{sex-1} mutant was reported by Yu et al.\(^ {24}\) The \textit{co-10} mutant was reported by Laubinger et al.\(^ {25}\) The \textit{co-2} mutant was reported by Simon et al.\(^ {29}\) The \textit{ft-10} mutant was reported by Jang et al.\(^ {30}\) The \textit{ft-7} mutant was reported by Onouchi et al.\(^ {31}\) The \textit{soc1-2} mutant was reported by Lee et al.\(^ {32}\) The \textit{gi-3} and \textit{gi-2} mutants were reported by Fowler et al.\(^ {18}\) Recombinant plant expressing fluorescent protein GBSS:GFP was described by Ortiz-Marchena et al.\(^ {10}\)

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**Figure 3.** Presence of GBSS protein \textit{in vivo} in different stages of seed (A–C) and lateral root development (D–F). pGBSS:GBSS:GFP plants were grown in LD and GFP presence was observed under the confocal microscope. Upper panel: GBSS presence in seeds in 3 different developmental stages (A) early seed, (B) medium stage seed and (C) mature seed. GFP fluorescence is associated to the aleurone cell layer in mature seeds. Lower panel: GBSS presence in root organs in different developmental stages: (D) early lateral root formation, (E) late stage lateral root formation, (F) root hairs. GBSS is progressively associated to the columella cell layer of the lateral root meristem but is absent from root hairs.
Starch Analysis
Starch granules were extracted by a modification of the method described by Huber as described in Ortiz-Marchena et al. and Albi et al.

Determination of Soluble Sugars
Whole content of main soluble sugars (glucose, fructose and sucrose) were identified and quantified employing a high-performance anion-exchange chromatography protocol as described in Ortiz-Marchena et al.

Real-Time Q-PCR
Q-PCR was performed in an iQTM5 multicolor real-time PCR detection system from Bio-Rad as described in Ortiz-Marchena et al. Normalized data were calculated by dividing the average of at least 3 replicates of each sample from the candidate and reference genes. Primers for QPCR mRNA amplification for STANS and the evolution of plant photoperiodic signalizing were described in Ortiz-Marchena et al. and Albi et al.

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References
1. Bernier G, Havelange A, Houssa C, Petitjean A, Lejeune P. Physiological signals that induce flowering. The Plant Cell 1993; 5:1147-55; PMID:12271018; https://doi.org/10.1105/tpc.5.11.147
2. Corbesier L, Vincent C, Jang S, Fornara F, Fan Q, Seale I, Giakoumis A, Farrowa S, Gissos L, Turnbull C, Coupland G. FT protein movement contributes to long-distance signaling in floral induction of Arabidopsis. Science 2007; 316:1030-3; PMID:17644055; https://doi.org/10.1126/science.1141752
3. Lebon G, Wojnarowiez G, Holzapfel B, Fontaine F, Vallant-Gaveau N, Clement C. Sugars and flowering in the grapevine (Vitis vinifera L.). J Exp Bot 2008; 59:2565-78; PMID:18098810; https://doi.org/10.1093/jxb/ern135
4. Gomez LD, Gilday A, Feil R, Lunn JE, Graham IA. STANS and the evolution of plant photoperiodic signalizing were described in Ortiz-Marchena et al. and Albi et al.
5. Wahl V, Ponnu J, Schlereth A, Arrivault S, Lange-Masterson K, Morales B, Coupland G. FT protein movement contributes to long-distance signaling in floral induction of Arabidopsis. Science 2007; 316:1030-3; PMID:17644055; https://doi.org/10.1126/science.1141752
6. Merida A, Rodriguez-Galan JM, Vincent C, Romero JM. Expression of the granule-bound starch synthase I (Waxy) gene from snapdragon is developmentally and circadian clock regulated. Plant Physiol 1999; 120: 401-10; PMID:10366431; https://doi.org/10.1104/pp.120.2.401
7. Tenorio G, Orea A, Romero JM, Merida A. Oscillation of mRNA level and activity of granule-bound starch synthase I in Arabidopsis thaliana leaves during the diurnal cycle. Plant Mol Biol 2003; 51: 949-58; PMID:12777053; https://doi.org/10.1023/A:1023053420632
8. Serrano G, Herrera-Palau R, Romero JM, Serrano A, Coupland G, Valverde F. Chlamydomonas CON-TA: a circadian clock-controlled gene that regulates photoperiodic flowering in Arabidopsis and encodes a protein with several possible membrane-spanning domains. The EMBO J 1999; 18: 4679-88; PMID:10366431; https://doi.org/10.1104/pp.106.081885
9. Zygmunt T, Kuhl M, Ruiz MT, Ribiero-Pedro M, Valverde F, Baldina J, Reussa E, Miguea F, Preiss J, Romero, JM. Two Arabidopsis AP2 gluco-glycine pyrophosphorylase large subunits (APL1 and APL2) are catalytic. Plant Physiol 2008; 148: 65-76; PMID:18614708; https://doi.org/10.1104/pp.108.122846
10. Yu TS, Kofler H, Hausler RE, Hille D, Flugge UI, Zeeman SC, Smith AM. Starch: its metabolism, evolution, and biotechnological modification in plants. Annu Rev Plant Biol 2010; 61: 209-34; PMID:20192737; https://doi.org/10.1146/annurev-arplant-042809-112301
11. Blagojevic MA. Flower development pathways. J Cell Sci 2000; 113: 547-8; PMID:11018768
12. Bowler S, Lee K, Onouchi H, Samach A, Richard- son K, Morris B, Coupland G, Putterill J. GIGANTEA: a circadian clock-controlled gene that regulates photoperiodic flowering in Arabidopsis and encodes a protein with several possible membrane-spanning domains. The EMBO J 1999; 18: 4679-88; PMID:10366431; https://doi.org/10.1104/pp.106.081885
13. Park DH, Sonmez DE, Kim YS, Choy YH, Lim HK, Soh MS, Kim HJ, Kay SA, Nam HG. Control of circadian rhythms and photoperiodic flowering by the Arabidopsis GIGANTEA gene. Science 1999; 285: 1579-82; PMID:10477725; https://doi.org/10.1126/science.285.5433.1579
14. Romero-Campero FJ, Lucas-Reina E, Said FE, Soh MS, Kim HJ, Kay SA, Nam HG. Control of circadian rhythms and photoperiodic flowering by the Arabidopsis GIGANTEA gene. Science 1999; 285: 1579-82; PMID:10477725; https://doi.org/10.1126/science.285.5433.1579
15. Dalchau N, Baek SJ, Briggs HM, Robertson FC, Dodd AN, Gardner MJ, Stancombe MA, Miyamoto HD, Stan GC, Goncalves JM, et al. The circadian oscillator gene GIGANTEA mediates a long-term response of the Arabidopsis thaliana circadian clock to sucrose. Proc Nat Acad Sci U S A 2010; 110: 5104-9; PMID:20383174; https://doi.org/10.1073/pnas.100542108
16. Mitrag M, Kiauxel S, Johnson CH. The circadian clock in Chlamydomonas reinhardtii. What is it for? What is it for? Plant Physiol 2005; 137: 399-409; PMID:15710681; https://doi.org/10.1104/pp.105.052415
17. Searle I, Coupland G. Induction of flowering by season. Trends Plant Sci 2004; 9: 309-14; PMID:15165563; https://doi.org/10.1016/j.tplants.2004.04.007
18. Seale I, Coupland G. Induction of flowering by seasonal changes in photoperiod. The EMBO J 2004; 23: 1217-22; PMID:15014450; https://doi.org/10.1038/sj.emboj.7600117
19. Romero-Campero FJ, Lucas-Reina E, Said FE, Romero JM, Valverde F. A contribution to the study of plant development evolution based on gene co-expression networks. Front Plant Sci 2013 4: 291; PMID:23935602; https://doi.org/10.3389/fpls.2013.00291
20. Streib S, Zeeman SC. Starch metabolism in Arabidopsis. Arabidopsis Book 2012; 10: e0160; PMID:22339420; https://doi.org/10.1199/tab.1060
21. Zeeman SC, Kossmann J, Smith AM. Starch: its metabolism, evolution, and biotechnological modification in plants. Annu Rev Plant Biol 2010; 61: 209-34; PMID:20192737; https://doi.org/10.1146/annurev-plant.60.032809.112301
22. Blagojevic MA. Flower development pathways. J Cell Sci 2000; 113: 547-8; PMID:11018768
23. Bowler S, Lee K, Onouchi H, Samach A, Richard- son K, Morris B, Coupland G, Putterill J. GIGANTEA: a circadian clock-controlled gene that regulates photoperiodic flowering in Arabidopsis and encodes a protein with several possible membrane-spanning domains. The EMBO J 1999; 18: 4679-88; PMID:10465674; https://doi.org/10.1093/emboj/18.17.4679
24. Park DH, Sonmez DE, Kim YS, Choy YH, Lim HK, Soh MS, Kim HJ, Kay SA, Nam HG. Control of
28. Laubinger S, Marchal V, Le Gourrierec J, Wenkel S, Adrian J, Jang S, Kalajta C, Braun H, Coupland G, Hoeker U. Arabidopsis SPA proteins regulate photoperiodic flowering and interact with the floral inducer CONSTANS to regulate its stability. Development 2006; 133: 3213-22; PMID:16854975; http://dx.doi.org/10.1242/dev.02481

29. Simon R, Igeno MI, Coupland, G. Activation of floral meristem identity genes in Arabidopsis. Nature 1996; 384: 59-62; PMID:8900277; http://dx.doi.org/10.1038/384059a0

30. Jang S, Torii S, Coupland G. Genetic and spatial interactions between FT, TSF and SVP during the early stages of floral induction in Arabidopsis. Plant J 2009; 60: 614-25; PMID:19656342; http://dx.doi.org/10.1111/j.1365-313X.2009.03986.x

31. Onouchi H, Igeno MI, Perilleux C, Graves K, Coupland G. Mutagenesis of plants overexpressing CONSTANS demonstrates novel interactions among Arabidopsis flowering-time genes. The Plant Cell 2006; 12: 885-900; PMID:16852935; http://dx.doi.org/10.1105/tpc.12.6.885

32. Lee H, Suh SS, Park E, Cho E, Ahn JH, Kim SG, Lee JS, Kwon YM, Lee I. The AGAMOUS-LIKE 20 MADS domain protein integrates floral inductive pathways in Arabidopsis. Genes Dev 2008; 14: 2366-76; PMID:1995392; http://dx.doi.org/10.1101/gad.815609

33. Huber SC. Role of sucrose-phosphate synthase in partitioning of carbon in leaves. Plant Physiol 1983; 71:818-21; PMID:16662913; http://dx.doi.org/10.1104/pp.71.4.818

34. Albi T, Ortiz-Marchena, MI, Ruiz MT, Romero JM, Valverde F. Purification of starch granules from Arabidopsis leaves and determination of granule-bound starch synthase activity. Bio-protocol 2014; 4(23):e1316. http://www.bio-protocol.org/e1316

35. Ortiz-Marchena MI, Ruiz T, Valverde F, Romero JM. Determination of soluble sugars in Arabidopsis thaliana leaves by anion exchange chromatography. Bio-protocol 2014; 4(23): e1317. http://www.bio-protocol.org/e1317